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THE MINERAL QUALITY PROBLEM IN THE COLORADO RIVER BASIN. APPENDIX A. NATURAL AND MAN-MADE CONDITIONS AFFECTING MINERAL QUALITY

Environmental Protection Agency
Denver, Colorado

1971

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THE MINERAL QUALITY PROBLEM
IN THE COLORADO RIVER BASIN

APPENDIX A

NATURAL AND MAN-MADE CONDITIONS
AFFECTING MINERAL QUALITY

UNITED STATES
ENVIRONMENTAL PROTECTION AGENCY
REGIONS VIII AND IX

1971

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THE ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency was established by Reorganization Plan No. 3 of 1970 and became operative on December 2, 1970. The EPA consolidates in one agency Federal control programs involving air and water pollution, solid waste management, pesticides, radiation and noise. This report was prepared over a period of eight years by water program components of EPA and their predecessor agencies--the Federal Water Quality Administration, U.S. Department of Interior, April 1970 to December 1970; the Federal Water Pollution Control Administration, U.S. Department of Interior, October 1965 to April 1970; the Division of Water Supply and Pollution Control, U.S. Public Health Service, prior to October 1965. Throughout the report one or more of these agencies will be mentioned and should be considered as part of a single agency--in evolution.

PREFACE

The Colorado River Basin Water Quality Control Project was established as a result of recommendations made at the first session of a joint Federal-State "Conference in the Matter of Pollution of the Interstate Waters of the Colorado River and Its Tributaries," held in January of 1960 under the authority of Section 8 of the Federal Water Pollution Control Act (33 U.S.C. 466 et seq.). This conference was called at the request of the States of Arizona, California, Colorado, Nevada, New Mexico, and Utah to consider all types of water pollution in the Colorado River Basin. The Project serves as the technical arm of the conference and provides the conferees with detailed information on water uses, the nature and extent of pollution problems and their effects on water users, and recommended measures for control of pollution in the Colorado River Basin.

The Project has carried out extensive field investigations along with detailed engineering and economic studies to accomplish the following objectives:

(1) Determine the location, magnitude, and causes of interstate pollution of the Colorado River and its tributaries.

(2) Determine and evaluate the nature and magnitude of the damages to water users caused by various types of pollution.

(3) Develop, evaluate, and recommend measures and programs for controlling or minimizing interstate water pollution problems.

In 1963, based upon recommendations of the conferees, the Project began detailed studies of the mineral quality problem in the Colorado River Basin. Mineral quality, commonly known as salinity, is a complex Basin-wide problem that is becoming increasingly important to users of Colorado River water. Due to the nature, extent, and impact of the salinity problem, the Project extended certain of its activities over the entire Colorado River Basin and the Southern California water service area.

The more significant findings and data from the Project's salinity studies and related pertinent information are summarized in the report entitled, "The Mineral Quality Problem in the Colorado River Basin." Detailed information pertaining to the methodology and findings of the Project's salinity studies are presented in three appendices to that report - Appendix A, "Natural and Man-Made Conditions Affecting Mineral Quality," Appendix B, "Physical and Economic Impacts," and Appendix C, "Salinity Control and Management Aspects."

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CHAPTER I. INTRODUCTION

As a part of its overall study of the mineral quality problem, the Colorado River Basin Water Quality Control Project (Project) carried out a thorough review and analysis of past water quality data, and made detailed field investigations of present conditions. These studies included a thorough review of factors which affect mineral quality of streams, review of previous investigations of the mineral quality problem in the Colorado River Basin and other similar basins, a rigorous statistical analysis of existing mineral quality data, and extensive field studies to determine the location and magnitude of salinity sources throughout the Colorado River Basin.

This Appendix includes a discussion of the factors which affect mineral quality in streams, a description of the statistical methods utilized in the analysis of existing water quality data and a summary of the findings, a description of the methods employed in the field studies, and a summary of the findings regarding sources of mineral salts within the Colorado River Basin.

Detailed compilations, discussions, and interpretations of data obtained in the field studies are available in open file reports at the Project Office at the Federal Center, Denver, Colorado. Printouts of analytical results and field measurements have been furnished to the Conferees and are available for review at the Project Office.

CHAPTER II. FACTORS WHICH AFFECT MINERAL QUALITY OF STREAMS

A clear distinction exists between the two basic causes of salinity increases in streams. These may be referred to as the salt loading and salt concentrating effects. The former is associated with the discharge of additional mineral salts into the stream system in municipal and industrial wastes, in irrigation return flows, and in water from natural sources. In other words, the salt load returned to the stream is greater than that diverted thereby increasing the salt burden in the stream. In contrast, the salt concentrating effect occurs as a result of consumptive use of water. No mineral salts are added, but the salt concentration increases as a result of water lost from the stream system. Some of the salt loading and salt concentrating factors that influence water quality are discussed in the following section.

SALT LOADING EFFECTS

Municipal and Industrial

The use of water for domestic purposes increases the mineral content of water in several ways. Washing, bathing, and laundering, of beings and things, make use of the principle of solution and disposal of mineral matter. The human body concentrates the mineral constituents in the food and water which passes through the digestive system. Water is forced to live up to its reputation as the "universal solvent" in an endless variety of ways in domestic use.

Municipalities having surface supplies of domestic water may add to or subtract from the total salt burden carried by the affected stream, but the waste water returned to the stream always has a higher mineral concentration than that of the diverted water. Municipalities which have ground water supplies and discharge waste water to surface streams always add salt loads to the receiving streams.

Industrial use of water affects mineral quality of streams much the same way as municipal uses. Water is used in many processes which employ its solvent properties, and in others, such as floatation, where solution of mineral matter is a side effect. Many industries utilize ground-water supplies; and discharge waste water to surface streams thereby adding to their salt load.

Mining and milling industries may contribute salts through seepage from waste holding ponds, tailings piles, and direct discharge of process wastes. Many mines intersect fissures and pervious formations containing highly mineralized water which may discharge to surface streams.

Brines and brackish waters are often brought to the surface by oil and gas drilling operations and by producing wells. Existing regulations are inadequate from the standpoint of limiting the quality of water discharged to surface streams. Discharge of brackish oil field water to streams can contribute substantial salt burdens.

Mineral exploitation, such as oil shale processing and subsurface nuclear explosions, may contribute mineral salts to surface streams unless such activities are properly monitored and regulated.

Irrigation

Irrigation contributes salt loads to streams through return flows. Water is diverted from streams and applied to the land in varying amounts depending upon the type of crops being grown. Some of the diverted water is consumed by evaporation and transpiration and some is returned to the stream system by way of canal wasteways and surface drains. Some of the water seeps into the soil and may or may not find its way back to the stream from which it was diverted.

Sources of water entering the soil profile include seepage from conveyance systems, deep percolation from irrigated lands, and seepage from tail water and other wastes. Wherever this water is in prolonged contact with the soil, it tends to reach a chemical equilibrium with the soil. The result may be either the dissolution of salts from the soil profile or precipitation of salt in the soil profile. In the Colorado River Basin, evidence indicates that salts are generally dissolved from the soils. However, authorities differ in their estimates(1,2,3) of the amount of salts that will be dissolved and on the length of time solution will persist following the initiation of irrigation. Some believe that with proper irrigation practices, solution of salts will be inconsequential after a brief "initial leaching." On the other hand, it seems apparent that solution of salts will persist in some cases. Water may travel a considerable distance in its underground route back to the stream system. Thus, there is ample time for the water to approach a state of chemical equilibrium with the soil formation. Soils yield soluble minerals through the process of weathering and decomposition. The solution process will proceed as long as the water in contact with the soil has not attained chemical equilibrium with the soil mass.

The amount of soil material dissolved depends upon a number of factors, including the type of soil, the quality of applied water, the length of the flow path, and the partial pressure of carbon dioxide.

Out-of-Basin Diversions

Much of the service area for Colorado River water lies outside the confines of the Basin. The amount of water diverted from the Colorado River into adjoining basins is shown in the following tabulation.

Diverted To	Amount (Acre-feet/year)
Platte River Basin[1]	388,000
Arkansas River Basin[1]	71,000
Rio Grande River Basin[1]	2,000
Bonneville Basin[2]	103,000
Southern California[3]	4,425,000
Mexico[4]	1,580,000
Total	6,569,000

Diversions from the Upper Basin are generally made near the high mountains which serve as the source of the river's water supply. Water from these mountainous areas is generally of excellent quality (below 100 mg/l TDS). Thus, these diversions do not effectively reduce the salt load of the Colorado River system. On the other hand, Lower Basin waters are of relatively poor quality so that a substantial salt load is removed when water is diverted from the stream system. Where the diverted water is exported out of the Basin, as in the case of diversions to Los Angeles and to the Imperial and Coachella Valleys, the salt load is removed from the Colorado River Basin system. In these cases, a portion of the diverted supply must

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1/ Water Resources Data for Colorado, U. S. Geological Survey, 1967.
2/ Iorns, et al, U. S. Geological Survey Professional Paper 441.
3/ California Water Bulletin for 1966.
4/ International Boundary Water Commission Water Bulletin, 1963.

leave the receiving area in order to purge imported salts from the systems served. Future diversions to the Gila River Basin by way of the Central Arizona Project will remove salts from the surface stream system since there will be no return of water from this project to the Colorado River. Present and future diversions are discussed more fully in Appendix B of this report.

Natural Sources

The natural sources of salt may be classified as discrete or diffuse. Discrete, or point sources include springs, or seeps, which issue as a single flowing stream, or as a series of such streams within a relatively small area. In contrast, diffuse natural sources are characterized by salt accretions from large drainage areas. In the Colorado River Basin, diffuse sources are generally of much greater magnitude than point sources.

Point Sources

A significant portion of the salt load in the Colorado River Basin issues from saline mineral springs which occur throughout the Basin. In this report, flowing wells are treated as discrete sources of salinity.

Diffuse Sources

In the Colorado River Basin, virtually all the stream flow and much of the salt load arise in the form of spring runoff. Much more moisture falls on the uplands and high mountains than in the lowlands and valleys. Because of both an increase in precipitation and a decrease in evaporation with increasing elevation, the upland areas yield most of the runoff while the lowland areas yield almost no surface flow except during and immediately following storms.

A portion of the precipitation which falls on the land surface is evaporated, while some flows overland to enter nearby streams. Some of the water which percolates into the soil may subsequently rise by capillary action and evaporate. Soil moisture may likewise be transpired by plants, move to nearby streams, or enter the ground-water reservoir. In each case, except for direct evaporation, there is a potential mechanism for solution of salts from the soil. Overland flow may pick up soluble salts stranded at the soil surface by evaporation of the capillary water. Streamflow enters bank storage in times of high stream stage and while in bank storage, the water dissolves minerals from the alluvial soils. Salts dissolved may be concentrated by the removal of water through phreatic evaporation. During periods of low streamflow, water emerging from bank storage will contain the salts leached from the alluvial formations. Precipitation entering the soil may emerge far downstream as the mineralized flow of springs or wells, or it may emerge in nearby streams as upwelling ground-water. Salts contained in these flows have been leached from the soils and rocks enroute to the streams.

As a result of the interaction between soil and water, the mineral quality of a stream is closely related to the geology and soils of its drainage area. The upland areas of the Colorado River Basin are, for the most part, composed of crystalline rocks which are resistant to weathering and contain few soluble minerals. These factors coupled with the relatively large amount of precipitation and restricted leaching opportunity result in runoff with low concentrations of dissolved solids, although the total salt load per unit of contributing land area is relatively large. The lowland valleys were created by erosion and deposition of mineral solids.

Thus, water which comes in contact with valley soils dissolves deposited mineral salts and transports them to nearby streams. Formations in some of these areas yield relatively high concentrations of mineral salts. Examples of such formations include: the Paradox formation which is composed of halite, gypsum, and anhydrite; Mancos shale which contains abundant amounts of gypsum; and the saline facies of Tertiary lake beds. In the Upper Colorado River Basin, Iorns(4) has more extensively documented this relationship between the geology of various areas and mineral quality of streams in those areas.

SALT CONCENTRATING EFFECTS

The consumptive loss of water from the stream system reduces the amount of water available to transport incoming salt loads. As a result, water consumption increases the downstream concentration of salts. Ways in which salinity concentration may be increased by removal of water from the stream system are discussed briefly in the following sections.

Municipal and Industrial

A number of municipal and industrial uses cause salt concentrating effects. Thermal electric power plants are a good example of this form of mineral quality degradation. Such plants normally add very little salt to a stream. However, they deplete the supply of water by evaporation, thus concentrating mineral salts into an ever-decreasing volume of water. The residual salts are removed from the power plant by "blowdown" water from the system. If the "blowdown" is returned to the stream system, it will return a quantity of salt approximately equivalent to the amount withdrawn. Thus, the net effect of the power plant is to consume water without affecting the salt burden of the river. The result is an increase in mineral quality in the stream. However, even if the "blowdown" were excluded from the stream system, the power plant would also affect mineral quality. The nature of this effect is discussed in considerable detail in the following section.

Irrigation

Irrigation entails consumptive use of water through evaporation, transpiration, and through seepage losses, where these losses do not return to the stream system. Wherever such water losses occur upstream from significant salinity sources, they may be expected to cause mineral quality deterioration. Removal of water from the stream above a salinity source diminishes the amount of water available for dilution of salts from that source. The impact of that salinity source on stream quality will therefore be increased by the consumptive loss of water. Thus, any removal of flow from a stream, for any purpose will adversely effect downstream water quality. This relationship is frequently overlooked since there may be no effect in the immediate vicinity of the water-using activity. Since irrigation depletes a significant quantity of flow from the Colorado River system, the salt concentrating effect of irrigation is especially important. Records indicate that an excessive amount of water is applied to irrigated lands in some areas of the Colorado River Basin. One reason is that irrigators feel compelled to use all the water historically diverted in order to maintain their water rights. Another reason is the lack of widespread understanding of the amount of irrigation water required to meet evapotranspiration and salt balance requirements. A third factor is the inadequacy of most irrigation systems to operate in accordance with irrigation demands. These systems generally serve water on a "rotation" basis so that the irrigator must use water when it is available to him, rather than when his crops need it. Whatever the justification, excessive consumptive use of irrigation water causes a detrimental increase in the concentration of mineral salts in the Colorado River Basin.

Out-of-Basin Diversions

Exportation of water from the Colorado River Basin increases salt concentrations below the points of diversion in the same way as other stream depletions. This concentrating effect is partially offset by the removal of salt from the Basin, as explained previously. However, in the Upper Colorado River Basin, diversions generally occur in the headwaters areas where salt concentrations are relatively low. For this reason, the net effect of these exports is to increase downstream salinity levels through reduction in available dilution water.

In the Lower Colorado River Basin, the major out-of-Basin diversions are at Parker Dam where nearly a million acre-feet of water is diverted for distribution by the Metropolitan Water District of Southern California and at Imperial Dam where water is diverted to the Gila Gravity Canal and the All-American Canal for irrigation and domestic uses in southwestern Arizona and southern California. These diversions remove water which would otherwise be available for dilution of downstream salt loads; however, the detrimental effect is partly mitigated since they also remove large quantities of salt.

Most of the seven Basin States have elected to utilize a portion of their allocated share of Colorado River water outside the confines of the Basin's drainage area. Thus, excluding Mexico, some five million acre-feet of water are currently exported from the Basin. The major exports are in California and Colorado; however, other Basin States are actively developing means for exportation of a part of their allocated share of the Basin's water supply. These planned out-of-Basin diversions will serve water to regions in the vicinity of Cheyenne, Albuquerque, Salt Lake City, and the Phoenix-Tucson area. Planned increases in the amount of exportation are as follows: Colorado, 432,000 acre-feet; New Mexico, 110,000 acre-feet; Utah, 144,000 acre-feet; Wyoming, 22,000 acre-feet; Arizona, between 676,000 and 1,321,000 acre-feet. Thus, future out-of-Basin exports will account for about half of the water supply of the Colorado River Basin.

The increase in out-of-Basin diversions, particularly those in the Upper Basin, will result in further degradation of mineral quality in the Colorado River system unless some means are found for augmenting the Basin's water supply with good quality waters.

CHAPTER III. HISTORIC CHANGES IN WATER QUALITY

INTRODUCTION

Those concerned with water resources of the Colorado River Basin generally recognize that changes have occurred in the mineral quality of surface waters of the Basin. This belief stems from the knowledge that development of the water resource projects and consumptive use of the water result in degradation of water quality. Although other studies of mineral quality of Basin streams have alluded to such changes, there has been no clear delineation of those changes which are associated with normal fluctuations in hydrologic patterns and those changes which can be attributed to man's activities.(4,5) The Project attempted to fulfill this need by rigorous application of standard statistical tests to the mass of historical data that has been compiled.

The Project's statistical analysis of existing mineral quality data was designed to:

(1) Identify the statistically significant changes in mineral quality with respect to time and distance.

(2) Provide a basis for development of sound conclusions regarding relationships to natural and man-made hydrogeological factors.

(3) Assist in the selection of points and/or stream reaches where additional sampling was needed.

CHANGES IN WATER QUALITY WITH RESPECT TO TIME

Statistical Methods Employed

Long-term mineral quality data developed by the U. S. Geological Survey, the Metropolitan Water District of Southern California, and the

Agricultural Research Service were utilized in the study. Quality and streamflow data from twenty-seven stations representing 353 station-years were analyzed. Many of the records dated from the early 1940's and a few began in the late 1920's. In all cases, the most recent data utilized was for water year 1963.

Preparation of Input Data. Total dissolved solids (TDS) or total filterable residue was chosen as the parameter of interest. The total dissolved solids determination is a broad analytical procedure encompassing all of the constituents involved in salinity concentrations in a stream. Moreover, TDS was the only parameter, other than pH or specific conductance, which was reported continuously throughout the periods of record for each sampling location.

Since the analytical results reported for any individual sample may have represented a variable time period based upon the collecting agency's procedures at the time of collection, it became necessary to develop a common time base for total dissolved solids concentration at all stations. The most logical time base appeared to be the 30-day month, since very few samples were composited for longer periods and the use of monthly values still permitted input of sufficiently large numbers of values for the statistical analysis.

Two methods of deriving a representative TDS value for each 30-day month were considered. The flow-weighted mean concentration may be thought of as representing the composition of all the water that passed the sampling point during the period of interest and it is approximately the result that would have been obtained if all the water had been retained in a reservoir and thoroughly mixed before analysis. The time-weighted average is most meaningful from the standpoint of the user who has a constant water demand and where the effect of variable flow is not important.

To meet the overall objectives of the study, the flow-weighted monthly mean TDS concentration was selected as most suitable for the input statistic. These values were obtained or calculated for each month of the period of record for all stations. The monthly mean TDS values through water year 1957 were taken from USGS Professional Paper No. 441 for stations in the Upper Colorado River. For water years 1958 through 1963 and for all stations in the Lower Colorado River Basin, these values were computed from USGS Water Supply Papers and other historical records. It was necessary to synthesize TDS values representing short periods where gaps in the data would have otherwise rendered the record unusable. This was accomplished by the use of flow-quality plots or the TDS-specific conductance ratio.

Specific Analytical Techniques. The analysis of variance and the "Student t Test" which were employed have as one of their basic assumptions the normal distribution of the population to be tested.(6) In nature, few phenomena are characterized by true normal distributions. The reason for this, in many cases, is the impossibility of negative values. Fortunately, moderate departure from normal does not significantly affect the use of more statistical tests which depend upon normal distributions of input data.

Preliminary examination of the data for unregulated streams of the Colorado River Basin revealed bimodal distributions of TDS concentrations. Examples of this type distribution are illustrated in Figures 1 time-weighted average is most meaningful from the standpoint of the user who has a constant water demand and where the effect of variable flow is not important.

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Specific Analytical Techniques. The analysis of variance and the "Student t Test" which were employed have as one of their basic assumptions the normal distribution of the population to be tested.(6) In nature, few phenomena are characterized by true normal distributions. The reason for this, in many cases, is the impossibility of negative values. Fortunately, moderate departure from normal does not significantly affect the use of more statistical tests which depend upon normal distributions of input data.

Preliminary examination of the data for unregulated streams of the Colorado River Basin revealed bimodal distributions of TDS concentrations. Examples of this type distribution are illustrated in Figures 1

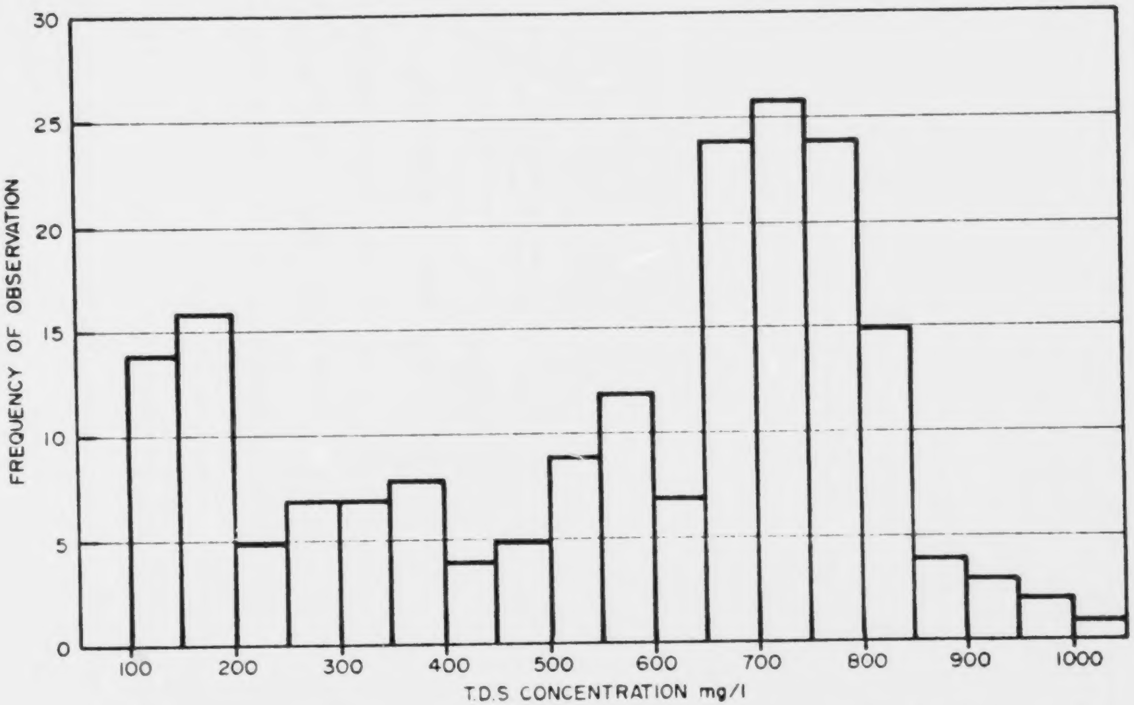

Figure 1 Distribution of Monthly Mean TDS Concentrations for the Eagle River at Gypsum, Colorado

and 2 for the Eagle River at Gypsum, Colorado, and Colorado River near Cisco, Utah. Bimodal distributions, such as those illustrated, indicate that two different populations were sampled. Most of the low TDS concentrations are associated with the high spring runoff flows; whereas TDS values associated with the second peak on the plots are for the low streamflow months.

Examination of the monthly mean discharge data for each of the unregulated streams indicated that the greatest portion of the spring runoff occurred in the months of May and June. The runoff period often extended into April or July, but only rarely to any other month. Therefore, the water quality data for each year were separated into periods of similar flow. The first period included those months associated with the high TDS concentrations, or those months where the streamflow did not include the spring runoff. The months of August through March were found to exclude the spring runoff at all stations included in this study, and are referred to hereafter as the "base flow months." This grouping of monthly TDS data exhibits a nearly normal distribution as shown in Figures 3 and 4. The "base flow" data, then, was found to be suitable for analysis by standard parametric tests including analysis of variance and the "t" test.

The second grouping of TDS concentrations represented the months of April, May, June, and July. A histogram of these values for the Eagle River at Gypsum, Colorado, is presented in Figure 5. It is evident from this plot that the distribution is considerably skewed toward the lower values. At most of the sampling locations studied, April and July are in effect transition months. Their inclusion into either period would

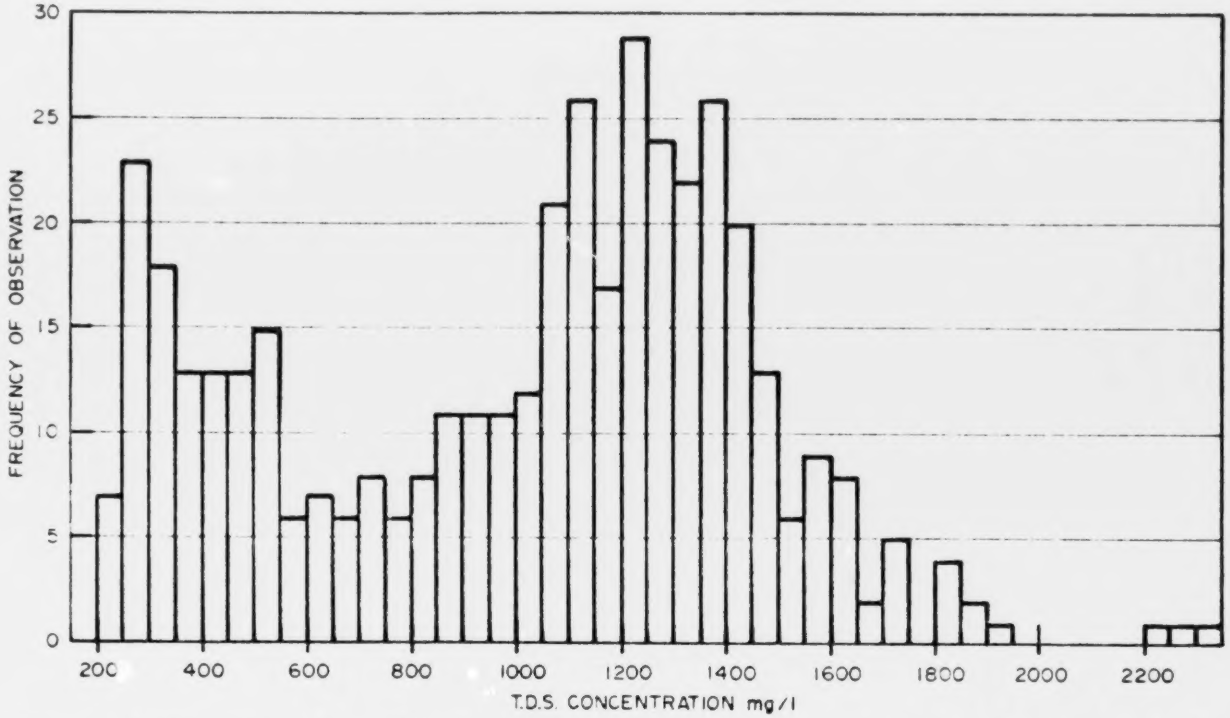

Figure 2 Distribution of Monthly Mean TDS Concentrations for the Colorado River near Cisco, Utah

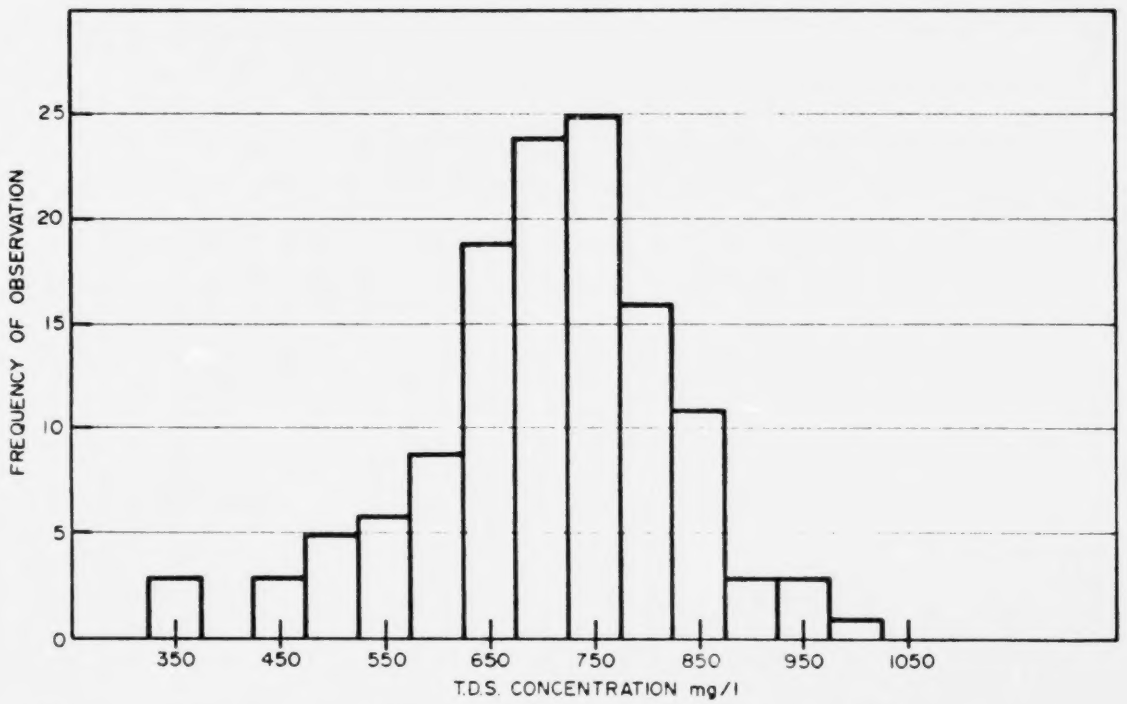

Figure 3 Distribution of Monthly Mean TDS Concentrations for Base Flow Months for the Eagle River at Gypsum, Colorado

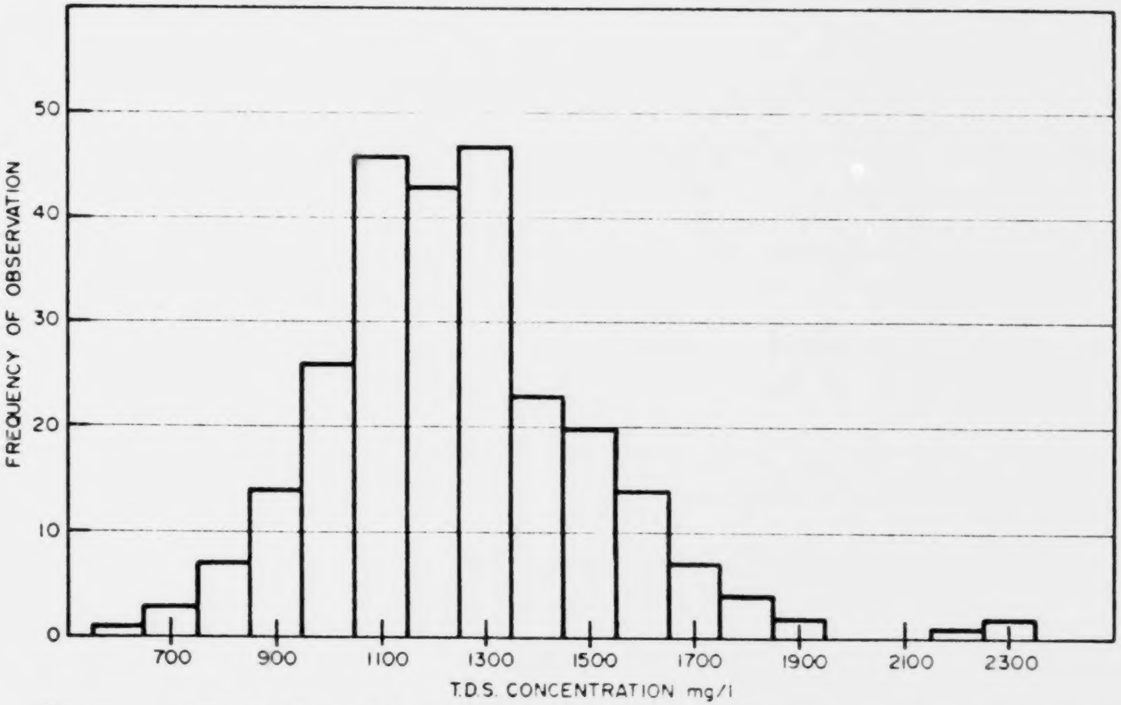

Figure 4 Distribution of Monthly Mean TDS Concentrations for Base Flow Months for the Colorado River near Cisco, Utah

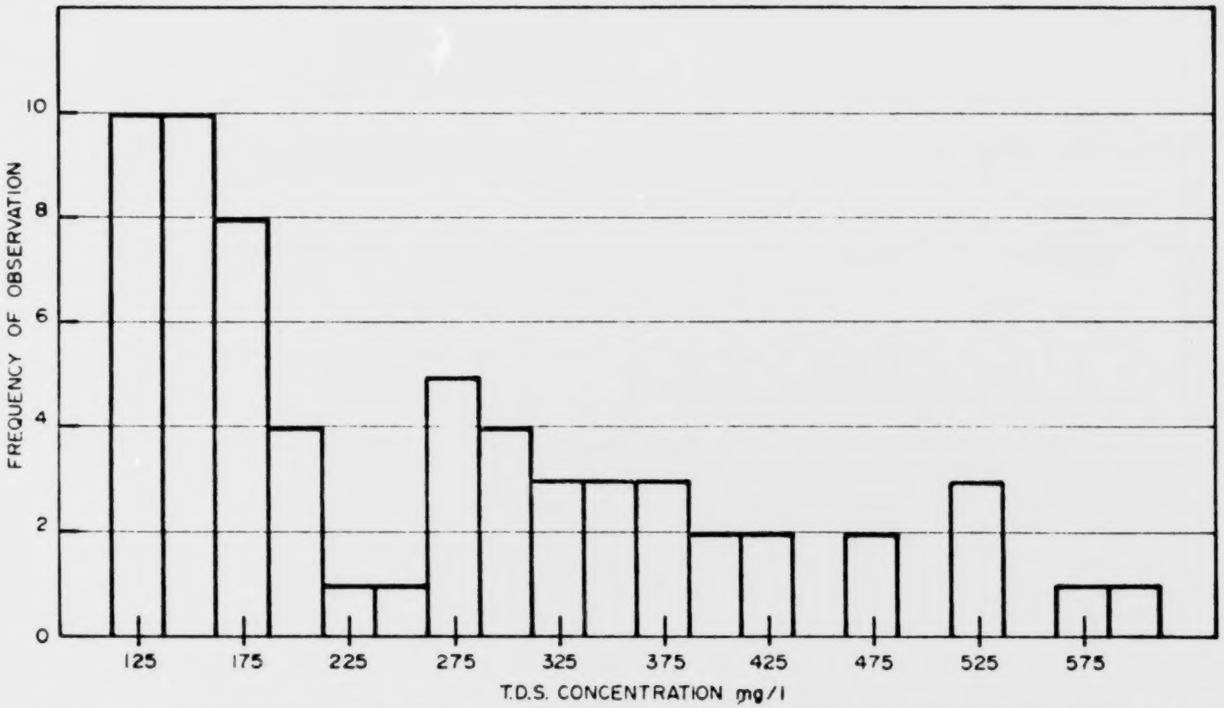

Figure 5 Distribution of Monthly Mean TDS Concentrations for April, May, June, and July for the Eagle River at Gypsum , Colorado

not have presented a true picture of changes that may have occurred. Moreover, the exclusion of the transition months from either the runoff or base flow periods should not affect the detection of changes in quality since any significant change, if present, would have been demonstrated in the two clearly defined periods. Therefore, the data representing the transition months of April and July were not used in the analysis of changes in quality with time, and, for the purposes of this study, May and June were designated as "runoff months."

Histograms of the TDS concentrations during the runoff months are presented in Figures 6 and 7 for the Eagle River at Gypsum, Colorado, and the Colorado River near Cisco, Utah. The distribution of TDS values for the runoff months does not approximate a normal distribution but is skewed toward zero. Parametric tests are not appropriate for analysis of this type of data. Therefore, the median test, a non-parametric method of testing for differences in means was utilized for analysis of data for runoff months.

The classifications described above are only applicable to data for unregulated streams. Streamflow regulation changes the distribution of both flow and concentrations. Because of the large storage capacity of reservoirs, such as Lake Mead, and mixing effects therein, variations within any year of record tend to be considerably dampened. This is illustrated by the distribution of TDS concentrations for the Colorado River at Parker Dam, California-Arizona, for all twelve months as shown in Figure 8. Therefore, data for stations on the main stem of the Colorado River below Lake Mead were analyzed using all twelve months in the same manner as the base flow data for stations in the Upper Colorado River Basin.

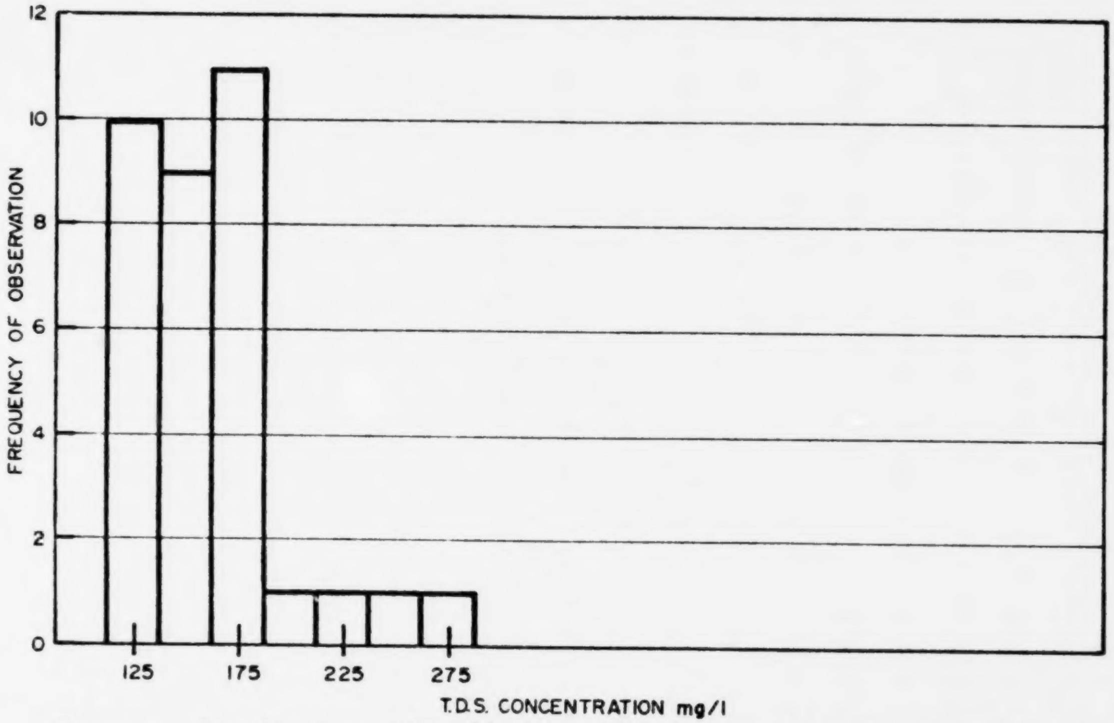

Figure 6 Distribution of Monthly Mean TDS Concentrations for Runoff Months for the Eagle River at Gypsum, Colorado

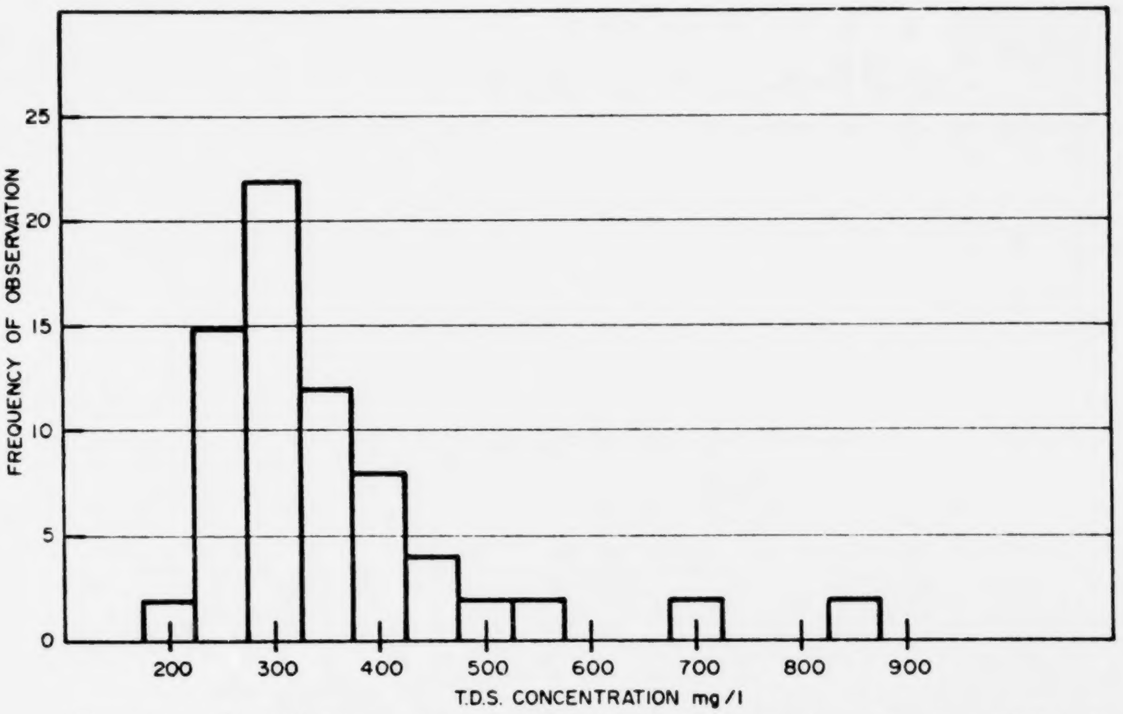

Figure 7 **Distribution of Monthly Mean TDS Concentrations for Runoff Months for the Colorado River near Cisco, Utah**

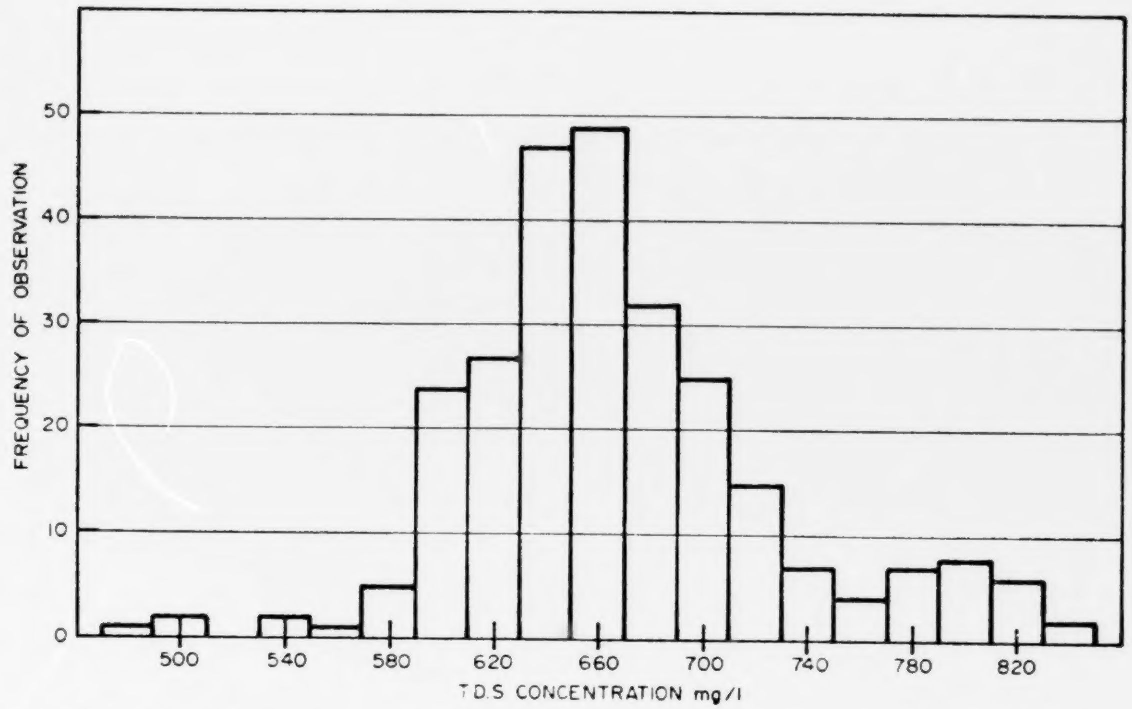

Figure 8 Distribution of Monthly Mean TDS Concentrations for the Colorado River at Parker Dam, California–Arizona

Double Mass Curve(7) techniques were employed to segregate periods of data for testing. In this application of the mass curve technique, the cumulative annual total TDS concentrations for either the runoff or base flow months are plotted against the corresponding years. This causes the time variable to be, in effect, cumulative. If no change in water quality occurred, over the period of record, then the data plots as a straight line and the slope of the line represents the mean concentration for that period. A break in the slope of the TDS mass curve indicates a change in the constant of proportionality between TDS and time, and the position of the break indicates the time at which the change occurred. The change in slope of the line at a break indicates the degree of change in water quality for the two periods.

Cumulative annual totals of the flow-weighted monthly mean TDS concentrations were plotted as percentages of the 1963 water year cumulation. This, in effect, normalized or placed all of the mass curves on a common base. Figure 9 is a typical mass curve of the type utilized in this analysis.[1/]

Mass curves were developed for both the runoff and base flow months on the unregulated streams and for complete years of data on the regulated streams of the Colorado River Basin.

It was necessary to exercise judgment in the selection of breaks representing changes in water quality and to ignore spurious breaks in the

---

[1/] All mass curves and other graphical analyses are on file in the Project Offices and are available for examination. The material is of such bulk that its inclusion herein is not practicable. The examples of these graphical techniques, provided herein, are intended to illustrate methods used in the statistical studies.

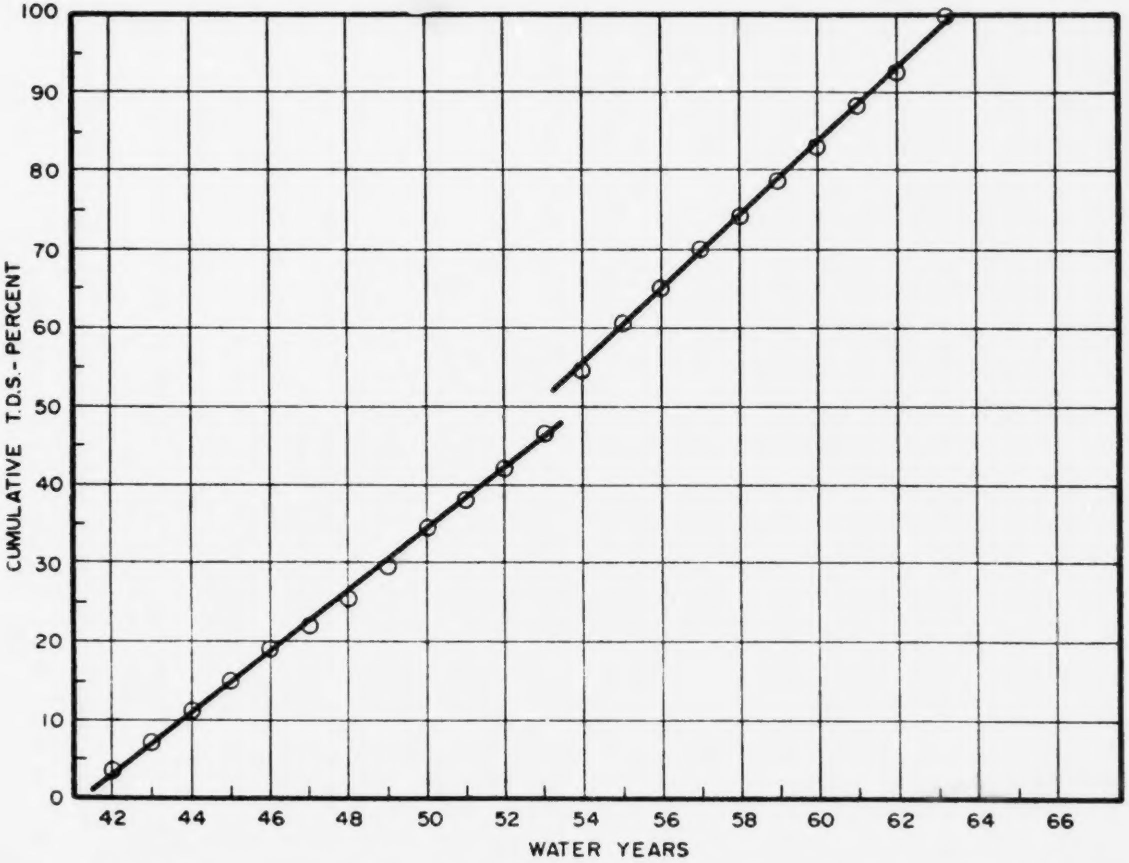

Figure 9 T.D.S. Concentration Mass Curve for the Colorado River near Glenwood Springs, Colorado

curve caused by the inherent variability related to short-term hydrologic patterns. Therefore, only those time periods representing changes of at least five years duration were tested.

In the statistical evaluation of the time patterns, the objective was to determine whether breaks in the mass curves corresponded to statistically significant changes in TDS concentrations. The hypothesis of significant difference between mean concentrations for two periods of time were tested by the "t" test. Since more than two apparent changes were to be tested, at most stations, the analysis of variance, or F-test, was the more appropriate analytical tool.

The F-test compares the variance, s_1^2, of each period tested with the pooled variance, s_2^2. In other words, the F-test is a special case of the "t" test wherein the variances are compared rather than the means. If the same random factors that cause variation within time periods are responsible for observed differences among time period means, then s_1^2 and s_2^2 will be equal within sampling limits. Therefore, the hypothesis tested with the F-test is that $s_1^2 = s_2^2 = \sigma^2$ or that,

$$F = \frac{s_1^2}{s_2^2} = 1$$

Usually the assumption is made that the alternative to $s_1^2 = s_2^2$ is $s_1^2 > s_2^2$, and the one-sided test is used.

The analysis of variance method of testing hypotheses is based upon the following assumptions: (1) that the samples come from a normally distributed parent population, (2) that variances of the populations are equal, (3) that the samples are random, and (4) that in cases of more than one variable of classification the effects are additive. If any of these conditions are not met there is uncertainty in tests of significance, particularly when the variance ratio is very near the critical value.

The assumption of randomness is always questionable in time series data. However, study of runoff for the Colorado River indicated that mean annual runoff can be considered random for periods of five years or more.(8) Since there is a correlation between salinity concentrations and runoff for most unregulated streams in the Colorado River Basin,(2,9) the assumption of randomness is reasonable where means representing periods of five years or more were compared.

The assumption of homogeneous variance was tested by the Bartlett's test which is described in most statistics textbooks.(10) If the populations are not normal, the Bartlett's test is not appropriate since rejection of the hypothesis could mean that the population variances are unequal and that the populations are not normal, or both. However, since this test is very sensitive to normality, acceptance of the hypothesis of equal variances also indicates that the data approximates a normal distribution.

The median test was utilized for the base flow months at those stations where the assumptions of normality and homogeneous variance were not satisfied. The number of cases in two samples, of size N_1 and N_2, falling above and below the median of the combined observations, $N = N_1 + N_2$, can be used to test the hypothesis that the samples are randomly drawn from two identically distributed populations. This test can be expanded for any number of samples and is not dependent upon normal distribution or homogeneous variances.

In cases where changes in quality appeared to be associated with changes in streamflow, three techniques were employed to confirm their association:

(1) Mass curve for stream discharge using a five-year moving average. This curve illustrates any change in trend in the runoff pattern with respect to time at each station. A five-year moving average was used to minimize the large variation in annual means which was exhibited at a number of stations.

(2) Percent of average flow graphs. The mean flow was calculated for the period of record for each station, and then the average flow for each year was converted to percentage of the mean flow for the period of record. These percentages were plotted on the TDS mass curves. Those years having greater than average annual streamflow for the period of record are represented by the area above the TDS mass curve line. The area bleow the mass curve indicates deficient runoff. Figure 10 illustrates the percent of average flow plots utilized in this technique.

(3) Spearman's Rank Correlation Coefficient.(6) This is a non-parametric test to determine the degree of correlation between two variables when the observations are taken at the same time. It is similar to the correlation coefficient of the least squares technique. It has been shown that most unregulated streams exhibit some flow-quality relationship. If a change in quality was due to a change in climatic conditions, then a flow-quality relationship should have prevailed during the period examined.

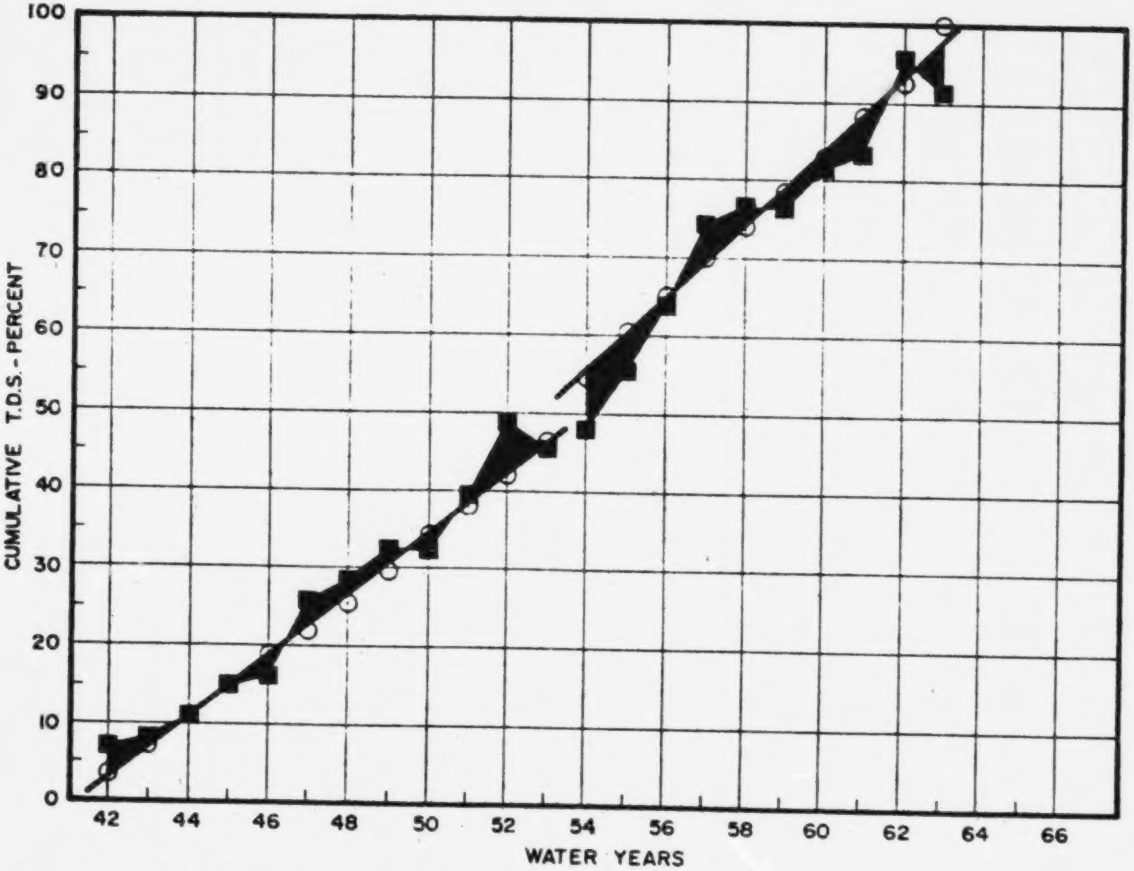

Figure 10 **TDS Concentration Mass Curve and Percent Average Flow for May and June, for the Colorado River near Glenwood Springs, Colorado**

Testing for significant changes in water quality, with respect to time, for the runoff months at each station was accomplished in a manner similar to that used for the base flow months. The major difference was in the use and interpretation of the analysis of variance since the assumptions of normality and homogeneity of variance could not be satisfied. The non-parametric median test was used as the statistical basis for decisions on the acceptance or rejection of the hypotheses of equal means for the time periods being considered.

The same procedures that were employed for the base flow months were followed in determining the causes of significant changes for the runoff months.

Results of Time Analyses

The time studies revealed that significant changes in mineral quality of Colorado River Basin streams, above Hoover Dam, occurred at eleven locations, during base flow months and at five locations during runoff months. Increases in mineral concentrations during base flow months were detected for the Colorado River at Hot Sulphur Springs, at Lees Ferry and at Grand Canyon; the Animas River at Farmington, New Mexico; and the San Juan River near Bluff, Utah. Statistically significant decreases in mineral concentrations were detected for the Colorado River near Cameo, Colorado, near Cisco, Utah, and Grand Canyon, Arizona; the Gunnison River near Grand Junction, Colorado; the White River near Watson, Utah; and the San Rafael River near Green River, Utah.

Increases in mineral concentrations during runoff months occurred for the Colorado River at Hot Sulphur Springs, Colorado, near Glenwood Springs, Colorado, near Cameo, Colorado, and near Cisco, Utah. No statistically significant decreases in mineral concentrations were detected during runoff months at Upper Colorado River Basin sampling stations.

All of the changes detected were definitely associated with changes in streamflow but only the 22 mg/l increase in TDS concentration for the Colorado River at Hot Sulphur Springs could clearly be associated with man-caused changes in flow. Closure of Willow Creek Dam of the Colorado-Big Thompson Project coincided with this increase.

All stations downstream of Hoover Dam exhibited statistically significant increases in mineral concentrations. These increases were associated with the drought of the mid-1950's, introduction of and subsequent improvements in the drainage of irrigated lands, the closure of dams and increased consumptive use. Decreases in mineral concentrations were detected at all stations below Hoover Dam at the conclusion of the drought.

Results of the time analyses are summarized in Tables 1, 2, and 3. Detailed discussions of these analyses are available in an open file report at the Project Office(11).

CHANGES IN WATER QUALITY WITH RESPECT TO DISTANCE

The objective of the distance analysis was to ascertain the significance of changes in mineral quality between sampling locations on streams in the Colorado River Basin. The study was also intended to single out reaches of streams in which significant increases in TDS concentrations occur. Such reaches would then be studied on a more intensive basis to identify the sources of salinity.

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Table 1. Changes in Water Quality at Sampling Stations in th
Above Hoover Dam During the Base Flow Month

Station Location	Period of Years		TDS Mean for Period (mg/l)	Analysis of Variance		Bartlett's Test	
	From	To		Observed F Value	Critical F Value 95%	Observed F Value	Critical F Value 95%
Colorado River at Hot Sulphur Springs, Colorado	48	53	85	41.46	3.92	2.09	3.84
	54	63	93				
Eagle River at Gypsum, Colorado	48	58	720	3.20	3.92	2.29	3.84
	59	63	679				
Colorado River near Glenwood Springs, Colorado	42	54	436	0.26	3.84	0.67	3.84
	55	63	430				
Colorado River near Cameo, Colorado	34	44	793	43.96	3.84	2.64	3.84
	45	63	698				
Gunnison River near Grand Junction, Colorado	32	40	1,530	30.18	3.84	21.54	3.84
	41	63	1,290				
Dolores River near Cisco, Utah	52	63	2,250	Variable - no 5-year trends			
Colorado River near Cisco, Utah	29	30	1,090	Not included in significance test			
	31	44	1,370	29.72	3.84	2.70	3.84
	45	63	1,210				
San Juan River near Archuleta New Mexico	56	63	263	Insufficient record			
Animas River at Farmington, New Mexico	41	50	471	32.27	3.84	6.11	3.84
	51	63	559				
San Juan River near Bluff, Utah	30	50	757	19.89	3.84	0.55	3.84
	51	63	841				
Green River near Green River, Wyoming	52	58	477	3.20	4.00	0.09	3.84
	59	63	441				
Henry's Fork at Linwood, Utah	52	56	1,235	0.26	4.00	2.45	3.84
	56	63	1,193				
Green River near Greendale, Utah	57	63	552	Insufficient record			
Yampa River near Maybell, Colo.	51	63	311	Straight line on Mass Curve			
Little Snake River near Lily, Colorado	51	56	532	0.13	3.92	2.00	3.84
	57	63	516				

B

ity at Sampling Stations in the Colorado River Basin
m During the Base Flow Months (August-March)

iance cal e 95%	Bartlett's Test Observed F Value	Bartlett's Test Critical F Value 95%	Median Observed χ^2	Median Critical χ^2-95%	Rank Correlation Coefficient Flow & Quality	Probable Cause of Change or Remarks
2	2.09	3.84			+0.05 -0.18	Willow Creek Dam of the Colorado-Big Thompson Project
2	2.29	3.84			-0.59	No change
4	0.67	3.84			-0.77	No change
4	2.64	3.84			-0.85	Drought of the 1930's
4	21.54	3.84	16.25	3.84	-0.36	Drought of the 1930's
5-year trends						No change
n significance test						
4	2.70	3.84			-0.61 -0.70	Drought of the 1930's
ecord						Insufficient record
4	6.11	3.84	27.09	3.84	-0.85 -0.83	Below average streamflow
4	0.55	3.84			-0.70	Below average streamflow
0	0.09	3.84				No change
0	2.45	3.84				No change
ecord						Insufficient record
on Mass Curve						No change
2	2.00	3.84				No change

Table 1. Contd. Changes in Water Quality at Sampling Stations i
Above Hoover Dam During the Base Flow Mo

Station Location	Period of Years From	Period of Years To	TDS Mean for Period (mg/1)	Analysis of Variance Observed F Value	Analysis of Variance Critical F Value 95%	Bartlett's Test Observed F Value	Bartlett's Test Critical F Value 95%
Duchesne River near Randlett, Utah	57	63	1,310	Insufficient record			
White River near Watson, Utah	51	57	622	4.63	3.92	1.98	3.84
	58	63	597				
Green River near Ouray, Utah	57	63	593	Insufficient record			
Price River at Woodside, Utah	52	63	3,990	Straight line on Mass Curve			
Green River at Green River, Utah	29	36	693	7.56	3.00	21.79	3.00
	37	46	753				
	47	63	709				
San Rafael River near Green River, Utah	48	57 (less 1950)	3,151	4.86	3.92	1.05	3.84
	58	63	2,863				
Colorado River at Lees Ferry, Arizona	48	53	965	4.88	3.92	5.46	3.84
	54	63	1,020				
Colorado River near Grand Canyon, Arizona	26	33	1,020	6.83	2.99	4.75	2.99
	34	41	1,130				
	42	63	1,060				

B

Quality at Sampling Stations in the Colorado River Basin
ver Dam During the Base Flow Months (August-March)

ariance tical lue 95%	Bartlett's Test Observed F Value	Critical F Value 95%	Median Observed χ^2	Critical χ^2-95%	Rank Correlation Coefficient Flow & Quality	Probable Cause of Change or Remarks
record						No Change
.92	1.98	3.84			-0.41	Drought of mid-1950's
record						Insufficient record
e on Mass Curve						No change
					-0.45	
.00	21.79	3.00			-0.46	
			14.86	5.99	-0.49	
					-0.77	Drought of mid-1950's
.92	1.05	3.84				
					-0.75	
.92	5.46	3.84			-0.73	Drought of mid-1950's
					-0.49	
.99	4.75	2.99	5.34	5.99 4.61(90%)	-0.71	Drought of mid-1930's

A

Table 2. Changes in Water Quality at Sampling Stat
Above Hoover Dam During the Runo

Station Location	Period Of Years From	To	TDS Mean for Period (mg/l)	Analysis of Variance Observed F Value	Critical F Value 95%	Median Observed χ^2	Critical χ^2-95%
Colorado River at Hot Sulphur Springs, Colorado	48	52	56	23.14	4.17	11.78	3.84
	53	63	78				
Eagle River at Gypsum, Colorado	48	53	154	0.70	4.17	0.13	3.84
	54	63	165				
Colorado River near Glenwood Springs, Colorado	42	53	155	18.00	4.07	15.49	3.84
	54	63	212				
Colorado River near Cameo, Colorado	34	53	226	10.75	4.00	3.68	3.84
	54	63	274				(2.71)
Gunnison River near Grand Junction, Colorado	34	53	372	4.15	4.00	0.08	3.84
	54	63	439				
Dolores River near Cisco, Utah	52	63	400				
Colorado River near Cisco, Utah	29	53	329	5.06	3.99	3.43	3.84
	54	63	395				(2.71)
San Juan River near Archuleta, New Mexico	56	63	119				
Animas River at Farmington, New Mexico	41	49	163	6.53	4.08	4.47	3.84
	50	63	193				
San Juan River near Bluff, Utah	30	63	271				
Green River near Green River, Wyoming	52	58	244	0.57	4.26	0.17	3.84
	59	63	265				
Henry's Fork at Linwood, Utah	52	63	663				
Green River near Greendale, Utah	57	63	374				
Yampa River near Maybell, Colorado	51	56	106	1.24	4.26	0.16	3.84
	57	63	116				

Water Quality at Sampling Stations in the Colorado River Basin
ove Hoover Dam During the Runoff Months (May & June)

f Variance	Median		Rank Correlation	
Critical ' Value 95%	Observed χ^2	Critical χ^2-95%	Coefficient Flow & Quality	Probable Cause of Change or Remarks
4.17	11.78	3.84	-0.81 -0.66	Willow Creek Dam of the Colorado-Big Thompson Proj.
4.17	0.13	3.84	-0.78	No change
4.07	15.49	3.84	-0.76 -0.88	Drought of mid-1950's
4.00	3.68	3.84 (2.71)	-0.81	Drought of mid-1950's
4.00	0.08	3.84	-0.89	No change
				No change
3.99	3.43	3.84 (2.71)	-0.89	Drought of mid-1950's
				No change
4.08	4.47	3.84	-0.46 -0.90	Below average streamflow
				No change
4.26	0.17	3.84	-0.74	No change
				No change
				Insufficient record
4.26	0.16	3.84	+0.22	No change

A

Table 2. Contd. Changes in Water Quality at Sampling
Above Hoover Dam During the

Station Location	Period of Years		TDS Mean for Period (mg/l)	Analysis of Variance		Median	
	From	To		Observed F Value	Critical F Value 95%	Observed χ^2	Critica χ^2-95%
Little Snake River near Lily, Colorado	51	55	161	2.21	4.26	0.16	3.84
	56	63	147				
Duchesne River near Randlett, Utah	57	63	849				
White River near Watson, Utah	51	56	339	0.43	4.26	0.16	3.84
	57	63	321				
Green River near Ouray, Utah	57	63	247				
Price River at Woodside, Utah	53	57	3,084	2.43	4.35	1.65	3.84
	58	63	4,126				
Green River at Green River, Utah	29	40	290	3.10	3.15	1.30	5.99
	41	55	308				
	56	63	276				
San Rafael River near Green River, Utah	58	63	1,590				
Colorado River at Lees Ferry, Arizona	48	53	321	3.05	4.17	3.47	3.84
	54	62	366				
Colorado River near Grand Canyon, Arizona	26	52	355	5.08	4.00	0.07	3.84
	53	62	403				

13

d. Changes in Water Quality at Sampling Stations in the Colorado River Basin Above Hoover Dam During the Runoff Months (May & June)

Analysis of Variance		Median		Rank Correlation Coefficient Flow & Quality	Probable Cause of Change or Remarks
Observed F Value	Critical F Value 95%	Observed χ^2	Critical χ^2-95%		
2.21	4.26	0.16	3.84	-0.17	No change
					Insufficient record
0.43	4.26	0.16	3.84	-0.21	No change
					Insufficient record
2.43	4.35	1.65	3.84	-0.93	No change
3.10	3.15	1.30	5.99	-0.30	No change
					No change
3.05	4.17	3.47	3.84	-0.85	No change Closure of Glen Canyon Dam
5.08	4.00	0.07	3.84	-0.80	No change Closure of Glen Canyon Dam

A

Table 3. Changes in Water Quality at Sampling Stations in th
of the Colorado River Below Hoover D

tion Location	Period of Years From	To	TDS Mean for Period (mg/l)	Analysis of Variance Observed F Value	Critical F Value 95%	Bartlett's Test Observed F Value	Critical F Value 95%	Obs
orado River below Hoover Dam	36	42	712	18.46	3.00	102.1	3.00	
	43	54	660					
	58	63	675					
	55	57	801	Not included in significance test				
	43	54	660	26.22	3.84	1.51	3.84	
	58	63	675					
orado River at Parker Dam, rizona-California	42	48	672	31.96	3.00	9.47	3.00	
	49	54	624					
	58	63	657					
	55	57	771	Not included in significance test				
	49	54	624	23.76	3.84	0.07	3.84	
	58	63	657					
orado River at Imperial Dam, rizona-California	45	54	690	244.15	3.84	0.28	3.84	
	58	63	787					
	55	57	876	Not included in significance test				
orado River at Yuma, Arizona	27	34	930					
	35	39	781					
	40	49	731					
	50	54	676					
	55	57	880					
	58	60	779					
	61	63	2,238					
	40	49	731	32.82	3.84	5.08		
	50	54	676					

B

lity at Sampling Stations in the Lower Main Stem
e Colorado River Below Hoover Dam

ce 5%	Bartlett's Test Observed F Value	 Critical F Value 95%	Median Observed χ^2	 Critical χ^2-95%	Rank Correlation Coefficient Flow & Quality	Probable Cause of Change or Remarks
					-0.05	Filling period of Lake Mead
	102.1	3.00			-0.09	
					-0.07	Drought of mid-1950's and low level of Lake Mead
ignificance test					-0.12	
	1.51	3.84			-0.09	
					-0.07	
					+0.10	
	9.47	3.00			-0.10	Closure of Davis Dam
					-0.13	Drought of mid-1950's and low level of Lake Mead
ignificance test					-0.47	
	0.07	3.84			-0.10	
					-0.13	
	0.28	3.84			-0.37	Cessation of drought and drainage facilities at CRIR and PVID
					-0.53	Drought of mid-1950's and low level of Lake Mead
ignificance test						
						Prior to Hoover Dam
						Closure of Hoover, Parker, Imperial Dams, complete diversion of Gila River and MWD Aqueduct
						Equilibrium period
						Completion of Davis Dam
						Drought of mid-1950's and low level of Lake Mead
						Cessation of drought and increased drainage at CRIR and PVID
						Wellton-Mohawk drainage
	5.08					

In the study of the distance patterns, the five years of record immediately prior to water year 1964 were used in determining mean TDS concentrations. The five-year period was selected in order that the influences of wet and dry years might be eliminated and to assure that the data would be as nearly homogeneous as possible. The water quality data used in this portion of the study were grouped as "base flow" and "runoff months" in the same manner as in the time analysis.

The approach taken, in the distance pattern analysis, was somewhat different from that taken by Iorns, et al(4) in that no synthesized data were utilized and a uniform five-year time span was employed. These constraints were imposed in order to minimize the effects of climatological cycles and the non-uniform pattern of man's developmental activities in the Basin. Minor differences in qualitative results of Iorns' analysis and the Project are apparent; however, the results of both analyses lead to the same conclusions regarding distance patterns in the Upper Colorado River Basin. Iorns did not undertake a similar analysis in the Lower Basin.

Data representing sequential pairs of stations were subjected to analysis by parametric and non-parametric tests. The TDS mean concentrations for all stations on the Lower Colorado River differed significantly at the 95 percent confidence level. Even the 29 mg/l difference in mean TDS concentration for the runoff months between Lees Ferry and Grand Canyon was found to be highly significant.

The mean TDS concentrations at key stations on streams in the Colorado River Basin are presented in Table 4. The difference in concentrations for adjacent stations is obvious in most cases. The

Table 4. Mean TDS Concentrations for Key Stations in the Colorado River Basin Water Years 1959-1963

River	Location of Station	Base Months (mg/l)	All Months (mg/l)	Runoff Months (mg/l)
Colorado	Hot Sulphur Springs, Colo.	94		77
	Glenwood Springs, Colo.	402		208
	Cameo, Colorado	732		265
	Cisco, Utah	1,152		316
	Lees Ferry, Arizona	1,015		477(372)[a]
	Grand Canyon, Arizona	1,069		512(401)
	Hoover Dam, Arizona-Nevada		677	
	Imperial Dam, Arizona-Calif.		792	
	Yuma, Arizona		Changing	
San Juan	Archuleta, New Mexico	259		124
	Bluff, Utah	869		316
Green	Green River, Wyoming	441		265
	Greendale, Utah	557(533)		407(337) [a]
	Ouray, Utah	592		240
	Green River, Utah	722		276
Eagle	Gypsum, Colorado	679		156
Gunnison	Grand Junction, Colorado	1,220		408
Dolores	Cisco, Utah	2,140		464
Animas	Farmington, New Mexico	552		203
Henry's Fork	Linwood, Utah	1,200		615
Yampa	Maybell, Colorado	317		112
Little Snake	Lily, Colorado	532		147
Duchesne	Randlett, Utah	1,220		999
White	Watson, Utah	601		303
Price	Woodside, Utah	3,950		4,740
San Rafael	Green River, Utah	722		276

---

[a] Figures in parentheses are for water years 1959-62. Closure of Glen Canyon and Flaming Gorge Dams caused abnormally high TDS concentrations at downstream stations in 1963.

dendritic diagrams for the runoff months (Figure 11) and the base flow months (Figure 12) show the changes in mineral quality with respect to distance for streams above Lake Mead. The relationships between quality changes and distance for sampling locations downstream of Hoover Dam are shown in Figure 13. Increases in TDS concentration occur, generally, in progression downstream, except where inputs of higher quality water dilute the water in the receiving streams. Increases are most marked in those reaches where agricultural drainage exerts strong influence and where overland runoff contributes dissolved salts to the streams. Causes of changes in water quality, with respect to distance, are discussed in detail in Chapter IV of this Appendix.

SUMMARY OF FINDINGS

During base flow months (August through March), four stations located above Hoover Dam exhibited increases in TDS concentrations, four showed decreases, and two experienced both increases and decreases. TDS concentrations increased significantly at five stations above Hoover Dam during runoff months. There were no cases of statistically significant decreases in salinity during the runoff months at these stations. All of the Colorado River stations downstream of Hoover Dam showed both increases and decreases in TDS concentrations.

All of the changes in quality in the Colorado River Basin at stations above Hoover Dam were associated with changes in the streamflow. Only one of these changes in streamflow could be clearly associated with man's activities. Closure of Willow Creek Dam was associated with increases in TDS concentrations at downstream stations. Other changes appeared to be the result of drought periods of the early and middle 1930's and mid-1950's.

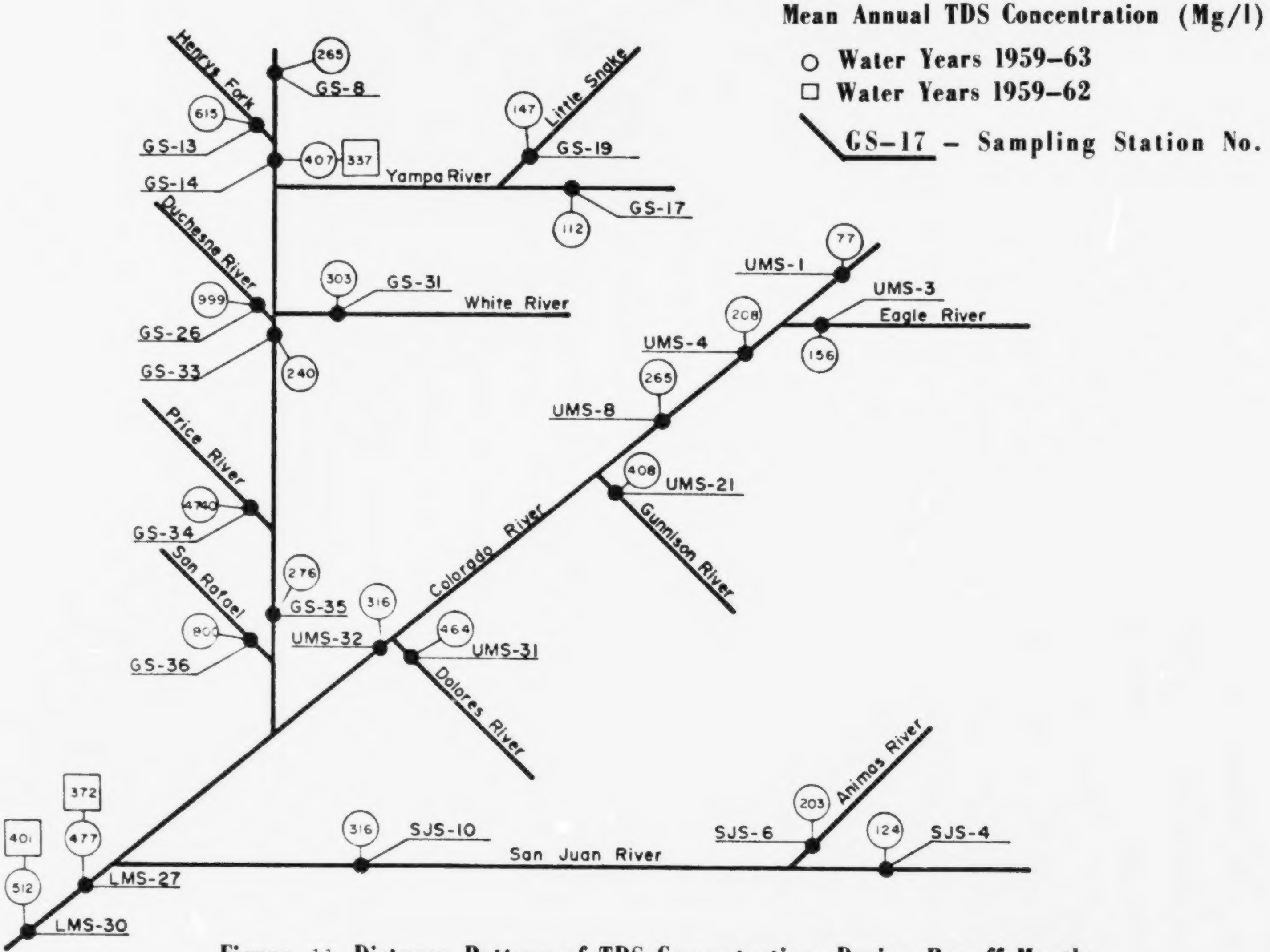

Mean Annual TDS Concentration (Mg/l)
○ Water Years 1959–63
□ Water Years 1959–62
GS–17 – Sampling Station No.
Henrys Fork
265
GS-8
615
GS-13
407
337
GS-14
Yampa River
147
Little Snake
GS-19
112
GS-17
Duchesne River
999
GS-26
303
GS-31
White River
GS-33
240
Price River
4740
GS-34
San Rafael
276
GS-35
800
GS-36
316
UMS-32
464
UMS-31
Dolores River
Colorado River
408
UMS-21
Gunnison River
265
UMS-8
208
UMS-4
77
UMS-1
UMS-3
Eagle River
156
372
477
401
512
LMS-27
LMS-30
316
SJS-10
San Juan River
203
SJS-6
Animas River
124
SJS-4

Figure 11 Distance Pattern of TDS Concentrations During Runoff Months for the Colorado River & Tributaries above Lake Mead

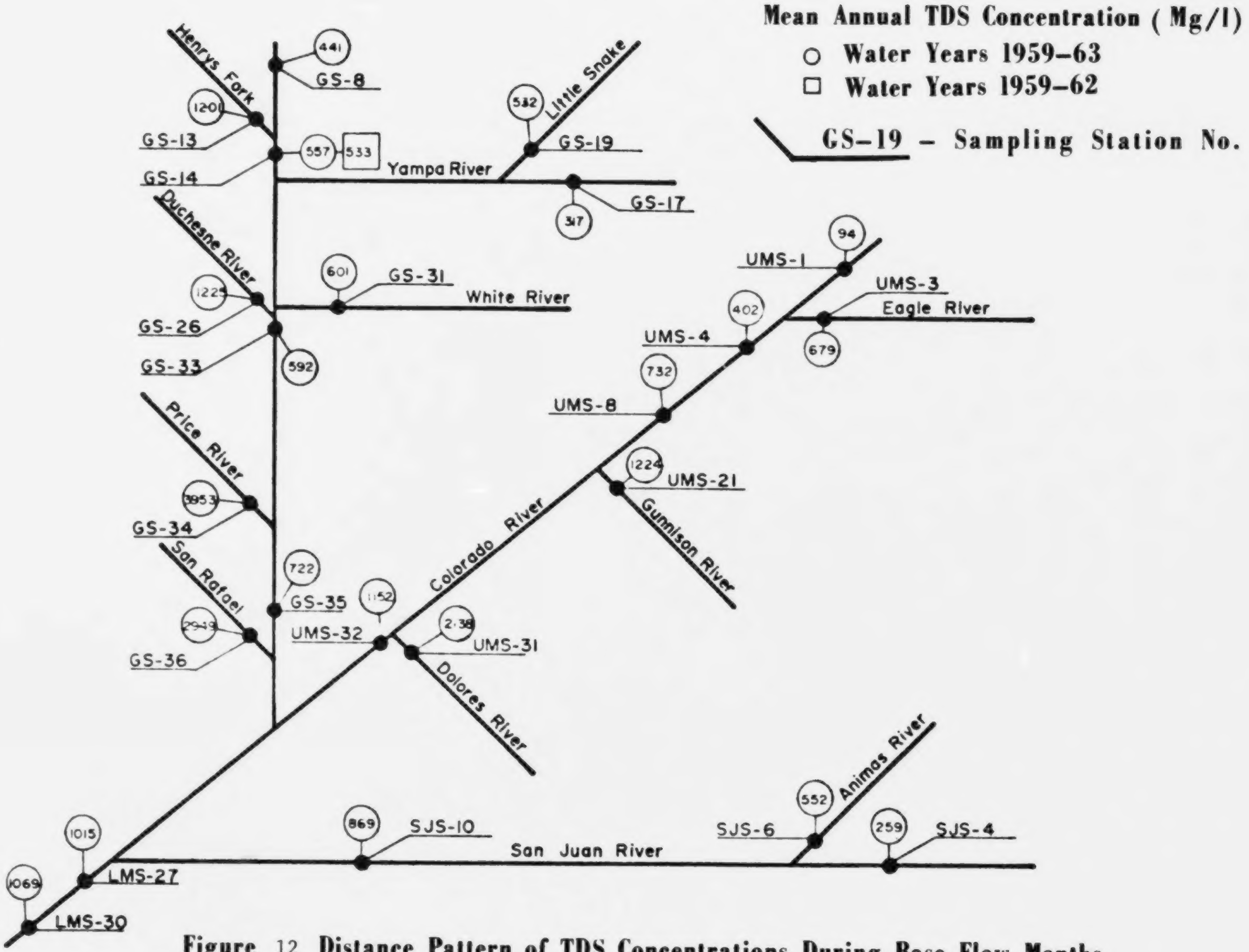

Mean Annual TDS Concentration (Mg/l)
○ Water Years 1959–63
□ Water Years 1959–62
GS–19 – Sampling Station No.
Henrys Fork
441
GS-8
1201
GS-13
557
533
GS-14
Yampa River
532
Little Snake
GS-19
317
GS-17
Duchesne River
1225
GS-26
601
GS-31
White River
GS-33
592
Price River
3853
GS-34
722
GS-35
San Rafael
2949
GS-36
94
UMS-1
UMS-3
Eagle River
679
402
UMS-4
732
UMS-8
1224
UMS-21
Gunnison River
Colorado River
1152
UMS-32
2138
UMS-31
Dolores River
1015
LMS-27
1069
LMS-30
869
SJS-10
San Juan River
552
Animas River
SJS-6
259
SJS-4

Figure 12 Distance Pattern of TDS Concentrations During Base Flow Months for the Colorado River & Tributaries above Lake Mead

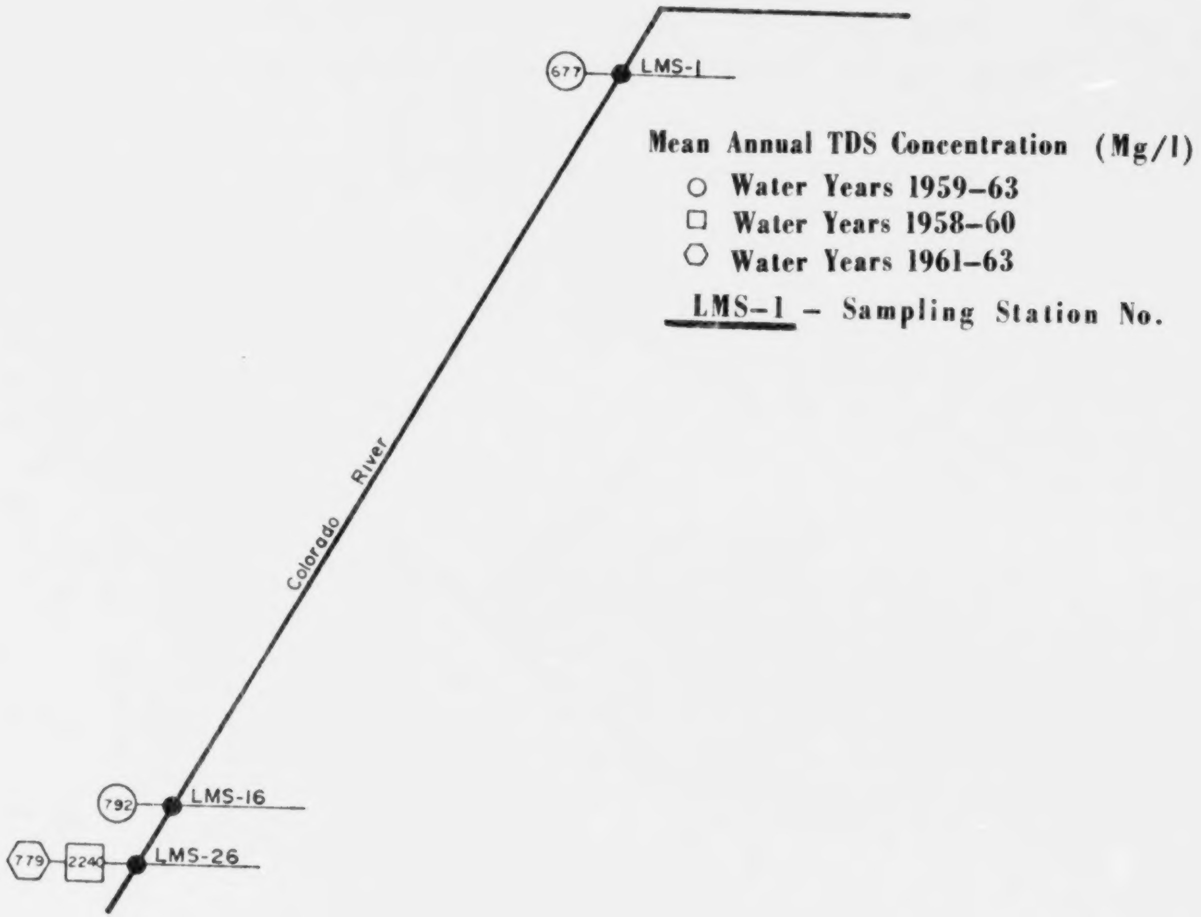

LMS-1
677
Mean Annual TDS Concentration (Mg/l)
○ Water Years 1959–63
□ Water Years 1958–60
⬡ Water Years 1961–63
LMS-1 – Sampling Station No.
Colorado River
LMS-16
792
LMS-26
2240
779

Figure 13 Distance Pattern of TDS Concentrations for the Colorado River below Hoover Dam

Changes in quality of the waters of the Colorado River downstream of Hoover Dam were found to be associated both with changes in streamflow and with the drainage from irrigated areas.

Analyses of the changes in water quality with respect to distance affirm that increases in TDS concentrations occur generally in downstream sequence, except where inputs of higher quality water dilute the water in the receiving streams. Increases are most marked in those reaches where agricultural drainage exerts strong influence and where overland runoff contributes dissolved salts to the streams.

CHAPTER IV. NATURE, LOCATION, AND MAGNITUDE OF SALINITY SOURCES

Several studies of mineral quality of water have been carried out in the Colorado River Basin. These include investigations by LaRue,(12) the U. S. Geological Survey,(4) and the Bureau of Reclamation.(13) These studies were based largely on existing water quality data, but incorporated the findings of special field studies in certain problem areas. Several Federal agencies, including the Bureau of Reclamation and the Geological Survey, have maintained long-term water quality surveillance programs, of varying intensity and techniques, throughout the Basin.

A detailed review of publications, reports, and unpublished information, by the Project staff, indicated certain gaps in existing data on mineral quality of the Basin's waters that needed to be filled in order to evaluate the changes in quality for certain reaches of streams. The Project, therefore, carried out short-term sampling programs and field investigations throughout the Basin to obtain data needed to fill major gaps in existing water data and to obtain detailed information on the location and magnitude of salinity sources. The Project studies included:

1. Detailed and intensive map and ground reconnaissance of the Colorado River Basin.
2. Study of geohydrology and stratigraphy of the Basin, and their effects on mineral quality of streams.
3. Evaluation of the effects of springs, seeps, diffuse natural sources, overland runoff, municipal and industrial discharges, and irrigation on mineral quality of streams.

4. Stream sampling and flow measurements to define stream reaches in which major changes in salinity and mineral composition occur.
5. Intensive water and salt budget studies of individual watersheds in the Upper Colorado River Basin, and of major irrigated areas adjacent to the Lower Main Stem of the Colorado River.

The studies were carried out in the Lower Colorado River Basin during the period November 1963 through December 1964, and in the Upper Basin from June 1965 through May 1966. The upper portions of the Little Colorado and Gila River drainage areas were not included in the studies since literature review and study of hydrological records indicated that these areas contribute insignificant amounts of flow and salt load to the Lower Colorado River. Except during infrequent floods, the Gila River has been discontinuous at Gillespie Dam since 1937. The river is reconstituted near the mouth by drainage from the Wellton-Mohawk Irrigation Project area. The effects of this drainage on mineral quality of the Lower Colorado River were included in the Project studies.

The waters in the upper portion of the Little Colorado River Subbasin are impounded and consumptively used to the extent that flow below Winslow, Arizona, becomes intermittent. Continuous flow is reestablished near the river's mouth by discharges from Blue Springs. Both the intermittent flow from the lower river reaches and the flow from the springs were included in the studies of the Lower Colorado River, but it was not possible to quantify the effects of irrigation in the headwaters area of the Little Colorado River.

In this Appendix, the term "Lower Colorado River Basin" is used to describe the drainage area which actually contributes significant flow to the Lower Colorado River. This excludes the reaches of the Little Colorado and Gila Rivers above the points at which the streams are discontinuous or intermittent.

FIELD STUDY METHODS

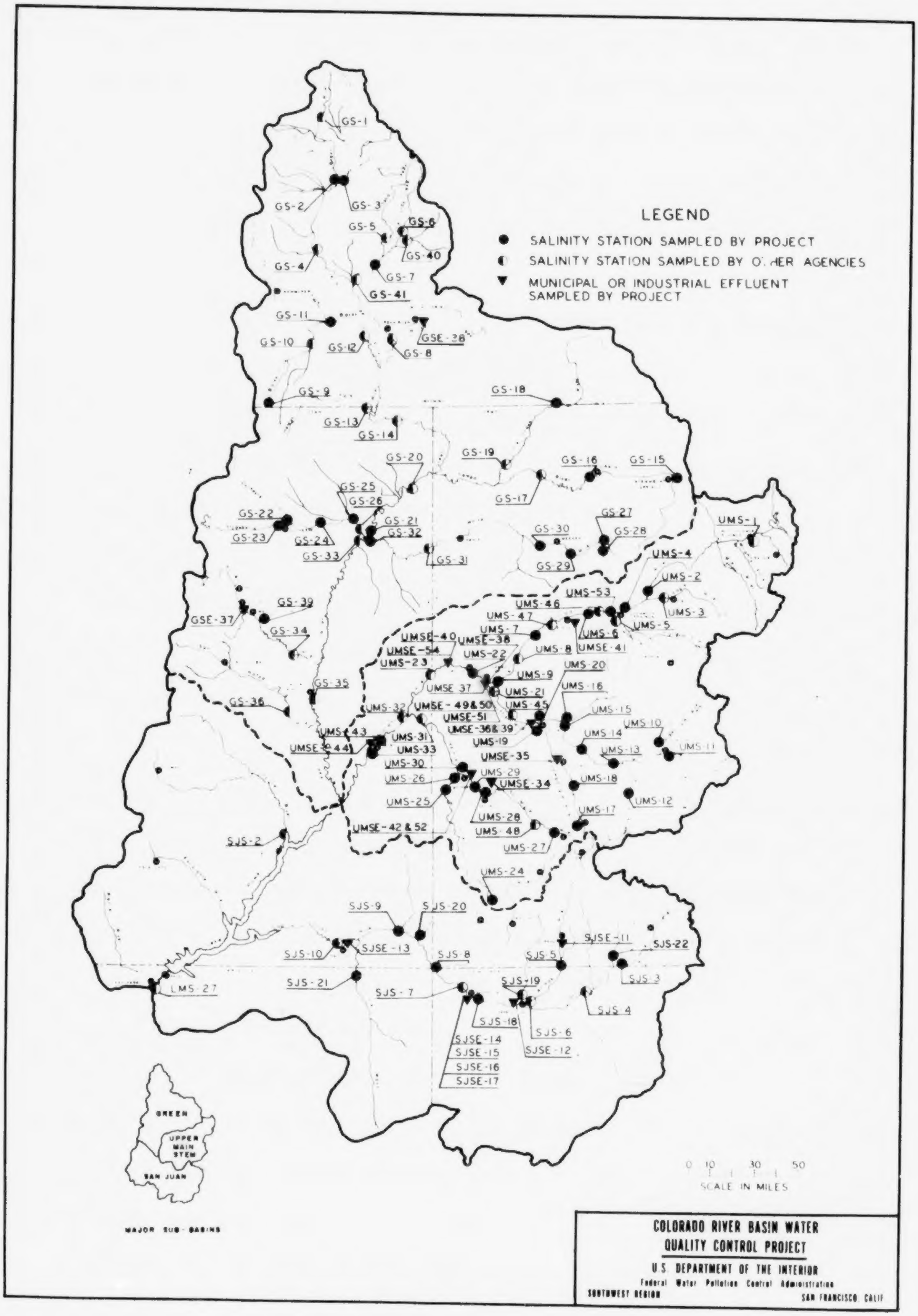
Collection of Basic Information

Basic information on irrigated acreage; cropping patterns; locations of springs and seeps; location, volume and quality of industrial waste discharges; quantity and quality of oil field brine and brackish water production; the effect of mine drainage; and other factors on mineral quality of Colorado River Basin streams was collected during the course of the field investigations. This information was obtained through interviews with responsible officials of irrigation districts, farm operators, county agents, State Engineers and staff, and faculty of agricultural schools, by detailed map and ground reconnaissance of streams and tributary areas, and by review and updating of municipal and industrial waste inventories. Project personnel made full utilization of the excellent information on geology, geohydrology, and stratigraphy of the Upper Colorado River Basin contained in the U. S. Geological Survey Report by Iorns and his associates.(4) Since no such compendium on Lower Colorado River Basin conditions was available, it was necessary for Project personnel to develop the water-related geological information for this area.

Water Quality Investigations

As indicated in Chapter III, various agencies, most notably the U. S. Geological Survey, have obtained mineral quality data at sampling stations throughout the Colorado River Basin. These sampling locations generally were selected to evaluate the effects of specific geohydrological factors or individual water resources projects. Data from these stations were of great value to the Project, but the stations did not provide sufficient areal coverage to meet Project objectives. Accordingly, the Project carried out a two-phase water quality-quantity study with the following principal features and objectives:

1. A network of sampling stations at key locations on principal streams within the Colorado River Basin. These stations, hereafter referred to as "main network stations" were located, insofar as possible, to provide measurement of salt loads entering and leaving significant watersheds, to define the magnitude of changes in mineral composition within critical reaches of streams, and to provide data for input to the Project's routing model studies. The locations of these stations in the Upper and Lower Colorado River Basins are shown on Figures 14 and 15, respectively.
2. Measurement of flow and mineral quality of selected streams, irrigation diversions and returns, and point sources of salinity. The stations sampled in connection with this activity are referred to, in this Appendix, as "survey stations." The Upper Colorado River Basin was subdivided into 29 watersheds or "study areas" for which salt and water budgets were developed. The locations of the 29 study areas are shown in Figure 16. Relative salt yields from these areas were evaluated in terms of the total salt load entering Lake Powell. The Lower Colorado River Basin studies were carried out in much the same manner. Budgets were developed for the reach between Lees Ferry and


LEGEND
● SALINITY STATION SAMPLED BY PROJECT
◐ SALINITY STATION SAMPLED BY OTHER AGENCIES
▼ MUNICIPAL OR INDUSTRIAL EFFLUENT SAMPLED BY PROJECT
GS-1
GS-2
GS-3
GS-4
GS-5
GS-6
GS-40
GS-7
GS-41
GS-11
GS-10
GS-12
GS-8
GSE-38
GS-9
GS-13
GS-14
GS-18
GS-19
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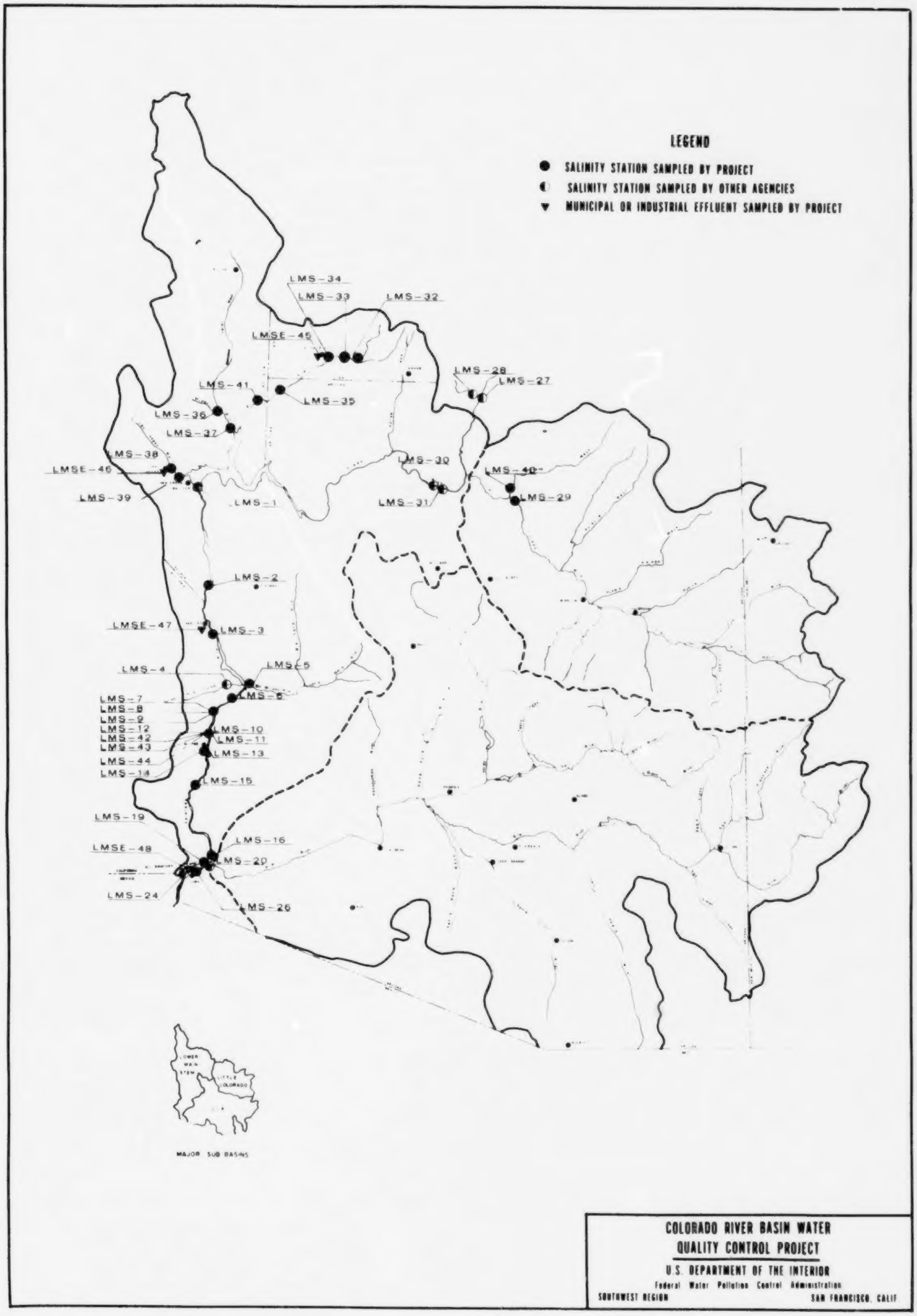
GS-27
GS-28
GS-39
GSE-37
GS-34
GS-35
GS-36
UMS-1
UMS-4
UMS-2
UMS-3
UMS-53
UMS-46
UMS-47
UMS-5
UMS-6
UMSE-41
UMS-7
UMS-8
UMSE-40
UMSE-38
UMSE-54
UMS-22
UMS-23
UMS-20
UMS-9
UMSE 37
UMS-21
UMS-16
UMS-32
UMSE-49&50
UMS-45
UMS-15
UMSE-51
UMSE-36&39
UMS-10
UMS-43
UMSE-44
UMS-31
UMS-33
UMS-19
UMS-14
UMS-11
UMS-13
UMSE-35
UMS-30
UMS-29
UMS-26
UMSE-34
UMS-18
UMS-25
UMS-12
UMS-28
UMS-17
UMSE-42 & 52
UMS-48
UMS-27
SJS-2
UMS-24
SJS-9
SJS-20
SJSE-11
SJS-22
SJS-10
SJSE-13
SJS-8
SJS-5
SJS-3
LMS-27
SJS-21
SJS-7
SJS-19
SJS-4
SJS-18
SJS-6
SJSE-12
SJSE-14
SJSE-15
SJSE-16
SJSE-17
GREEN
UPPER MAIN STEM
SAN JUAN
MAJOR SUB-BASINS
0 10 30 50
SCALE IN MILES
COLORADO RIVER BASIN WATER
QUALITY CONTROL PROJECT
U.S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF

Figure 14 Main Network Sampling Stations Upper Colorado River Basin


LEGEND
● SALINITY STATION SAMPLED BY PROJECT
◐ SALINITY STATION SAMPLED BY OTHER AGENCIES
▼ MUNICIPAL OR INDUSTRIAL EFFLUENT SAMPLED BY PROJECT
LMS-34
LMS-33
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LMSE-45
LMS-28
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LMS-37
LMS-38
LMSE-46
LMS-39
LMS-1
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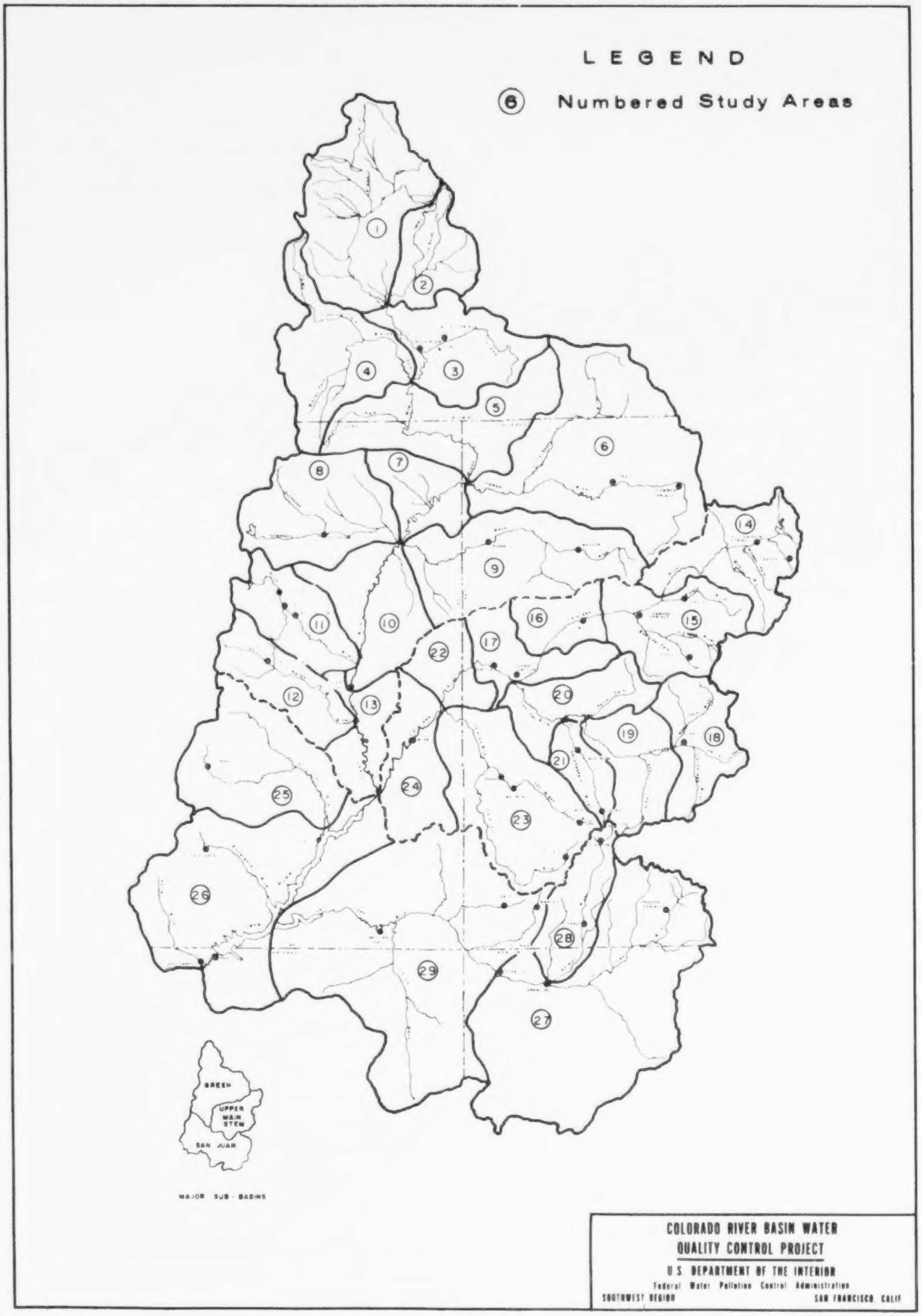
LMS-40
LMS-29
LMS-2
LMSE-47
LMS-3
LMS-4
LMS-5
LMS-6
LMS-7
LMS-8
LMS-9
LMS-12
LMS-42
LMS-43
LMS-44
LMS-14
LMS-10
LMS-11
LMS-13
LMS-15
LMS-19
LMSE-48
LMS-16
LMS-20
LMS-24
LMS-26
LOWER MAIN STEM
LITTLE COLORADO
MAJOR SUB BASINS
COLORADO RIVER BASIN WATER
QUALITY CONTROL PROJECT
U.S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF

Figure 15 Main Network Sampling Stations Lower Colorado River Basin


LEGEND
⑥ Numbered Study Areas
1
2
3
4
5
6
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8
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10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
GREEN
UPPER MAIN STEM
SAN JUAN
MAJOR SUB-BASINS
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U.S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF

Figure 16 Study Areas, Upper Colorado River Basin

Hoover Dam, and for the reach between Hoover Dam and the Northerly International Boundary. It was not possible to develop a budget for the reach between the Northerly and Southerly International Boundaries, known as the "Limitrophe Section."

Where possible, water quality stations maintained by the U. S. Geological Survey, the Bureau of Reclamation, and other State and Federal agencies were incorporated in the Project's field studies. Project sampling stations were located near existing USGS flow-measurement stations where possible. In situations where flow data were not available, Project personnel performed the necessary stream gaging and stage measurements.

Main network stations were sampled at two-week intervals. Samples were subjected to measurement of physical parameters in the field, and to complete[1/] mineral analysis at the Project laboratory in Salt Lake City, Utah.

Survey stations were sampled at monthly intervals and samples for alternate months were subjected to complete analysis. Specific conductance was measured on samples collected for intervening months. TDS-conductivity relationships developed at the survey stations were utilized to estimate TDS concentrations for the samples for which only conductivity was measured.

The study methods employed did permit differentiation between the salt concentrating and salt loading effects discussed in Chapter III of this Appendix. Although the distinction between the two effects is clear in the case of springs, some municipal and industrial effluents, and

---

1/ Calcium, Magnesium, Sodium plus Potassium, Chloride, Sulfate, Bicarbonate, residue at 180°C, pH, and Specific Conductance.

discharges of water used only for cooling, most of the results of this study represent the combined salt loading and salt concentrating effects.

Raw analytical data developed in the course of the field studies are too voluminous for inclusion in this Appendix. These data have been furnished to the Conferees, and to participating and cooperating agencies at periodic intervals. Printouts of the raw data are available for examination at the Project Office in Denver, Colorado.

Evaluation of Discrete Sources of Dissolved Minerals. Springs and seeps, for which salt loads were available in various reports and publications, were checked by field measurements. Salt yields were measured and documented for other springs which were located by field reconnaissance. Several abandoned oil-test wells were found to be discharging significant salt loads to Basin streams. An open file report, providing salient information on all known discrete natural sources of mineralized water in the Basin, has been prepared and is available in the Project Office.(14)

The salt loads contributed by municipal effluents were measured at thirteen representative communities within the Basin. The quantity and mineral quality of domestic water supplies, and of waste water discharged to surface streams, were determined. Based upon data obtained at the thirteen representative communities, salinity contribution coefficients (tons of salt per day per 1000 population) were developed and used in calculating salt loads for other communities throughout the Basin.

Salt contributions from industries having direct discharge of industrial wastes, process water, or cooling water to streams were documented by flow measurement and sampling at appropriate intervals. Salt loads contributed by discrete return flows in surface drains from irrigated areas were evaluated in the same manner.

The major producing oil fields within the Basin were surveyed on a well-by-well basis to determine the extent and magnitude of the salt loads attributable to disposal of produced water and other oil-field activities.

Coal and metals mining operations, and associated mills and refineries, were examined to ascertain their contribution of both mineral salts and heavy metals to Basin streams.

Evaluation of Diffuse Sources of Dissolved Minerals. Mineral quality data developed from sampling of network and survey stations were used to prepare water and salt budgets for the study areas. These budgets were then utilized to calculate the flow and total dissolved solids yields of unit areas. The technique used has been described by Iorns and his associates.(4) The Project studies, however, utilized quality and flow data for specific days, and included data for every known significant inflow within each area. Iorns' work was based upon mean values for fewer sampling stations.

The water and salt budgets were based upon data from all gaged and measured runoff[1/] to the stream system, runoff from ungaged tributaries, and measured outflows. The flow and salt loads for ungaged tributaries were derived by correlation with nearby gaged streams with appropriate adjustments for variation in geological characteristics and precipitation.

[1/] As used in this Appendix, the term "runoff" refers to all of the water flowing in the stream channel and includes surface runoff, interflow, and base flow. "Surface runoff" includes only the water that reaches the stream channel without percolating to the water table.(15)

The difference between the calculated input loads and flows and the measured outflow, from the areas studied, was attributed to leaching and seepage associated with irrigation, and direct overland runoff to streams. The magnitude of the direct overland runoff from most areas was insignificant except during periods of snowmelt. Field observations, streamflow records, and U. S. Weather Bureau records were used to obtain estimates of the periods and magnitude of overland runoff. Periods of irrigation diversions occurred only during summer and early fall months, and were thus easily distinguished from periods of snowmelt. Return seepage from irrigation which carried leached salts continued throughout the year in most areas.

For irrigated areas served by surface water supplies, water and salt budgets were structured so that only salt added to the streams by leaching was attributed to irrigation. Where areas were irrigated with ground-water, the entire salt load was attributed to irrigation since the dissolved minerals in the pumped ground-water in most cases would not have reached the immediate reach of stream in the absence of pumping for irrigation.

The water and salt budget method utilized in these studies is well suited to headwaters areas, where streamflow and quality are sensitive to small inputs of water and salt. The method is less suitable for downstream reaches where errors in flow measurement or laboratory analyses can mask or distort the calculated response to salt inputs. Owing to the very large diversions and the highly developed systems of irrigation drains, the Lower Colorado River Basin studies were treated in terms of the effect of each salt load input and diversion on the stream.

Outcrop patterns for the various geologic formations in the Upper Colorado River Basin are shown on U. S. Geological Survey bedrock geology maps for the Basin States. The geohydrologic characteristics of the pertinent formations are summarized on Plate No. 1 of USGS Professional Paper No. 441.(4)

Evaluation of Changes in Mineral Composition. Changes in the relative proportions of chemical constituents in water may occur with, or without, changes in the total dissolved solids content. Such changes may result from ion exchange, precipitation or solution of mineral compounds, or the addition of water having a different chemical composition. Composition changes between key sampling stations, and the relationship of composition of major inflows to that of receiving streams, were studied by the method outlined by Hem in USGS Water Supply Paper No. 1473.(5)

RESULTS OF FIELD INVESTIGATIONS - UPPER BASIN

A brief description of each of the study areas in the Upper Colorado River Basin and the significant findings of the field studies for each are presented in the following sections. Detailed discussions of each study area are contained in an open file report(16) which is available for inspection at the Project Office in Denver, Colorado.

Study Area 1 (Green River Subbasin)

Description. Area 1 consists of the Green River drainage upstream of Big Sandy Creek, which encompasses 4,922 square miles in Sublette, Lincoln, and Sweetwater Counties in Wyoming (Figure 17). Elevations range from 6,300 feet at the junction of the Green River and Big Sandy Creek to 13,785 feet on Gannett Peak in the Wind River Range.

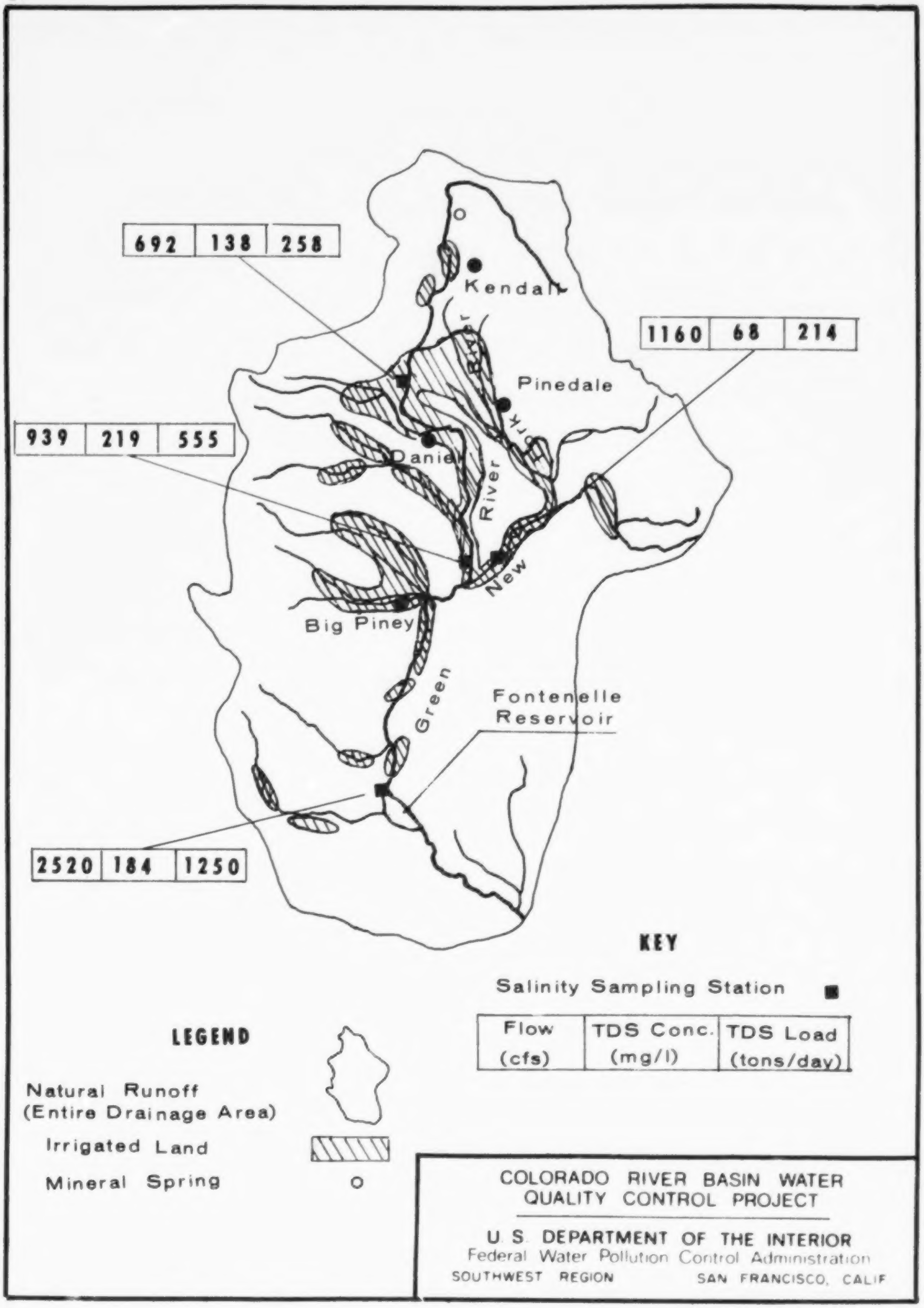
692 | 138 | 258
Kendall
1160 | 68 | 214
Pinedale
939 | 219 | 555
Daniel
New Fork River
River
New
Big Piney
Green
Fontenelle Reservoir
2520 | 184 | 1250
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land ▨
Mineral Spring ○
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U.S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF

Figure 17 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 1, Upper Colorado River Basin, 1965–66

The higher portions of the Wind River Range are composed of highly resistant igneous and metamorphic rocks. Precipitation on these uplands ranges from 20 to 50 inches per year. Because of the abundant precipitation and resistant characteristics of these areas, streams draining from them yield large flows of good quality water. The northern end of the Wind River Range and the entire Wyoming Range contain more soluble sedimentary rocks that were deposited during the Cretaceous age. Although there is less precipitation on these mountain ranges, the soluble rocks yield runoff having TDS concentrations of 200 to 1,000 mg/l. Most of Area 1 is underlain by Tertiary rocks which were deposited in a brackish lake. The old residual lake beds contain highly saline materials and yield base flow to streams having TDS concentrations of from 300 to 7,000 mg/l.

Findings. Most of the flow in streams of Area 1 originates in the higher mountain areas and is of excellent quality. Nearly all of the salt load contributed by the area is derived from the saline lake bed materials in the central portion of the area.

Two mineral springs near Kendall added 26 tons of salt per day. Irrigation of about 81,000 acres of hay and pasture land added approximately 30 tons of salt per day (Figure 17). The average salt contribution from irrigation was 0.1 ton per acre per year.

Ionic composition diagrams for streams of this area have the triangular shape which is characteristic of most headwaters streams in the Upper Colorado River Basin. A general increase in total dissolved solids concentration occurs between Warren Bridge and the mouth of the New Fork

River. Inflow from the New Fork River improved quality in the Green River downstream of the confluence of the two streams, but there were no important changes in the relative proportions of chemical constituents in streams of Area 1 (Figure 48).

The salt budget for Area 1 is shown in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Springs	26	2.1
Irrigation	30	2.4
Runoff	1194	95.5
Sub-Total	1250	
Decrease in Storage	160	
Net	1410	

Study Area 2 (Green River Subbasin)

Description. Area 2 covers approximately 1,720 square miles in Sublette, Fremont, and Sweetwater Counties in Wyoming, and includes the entire drainage area of Big Sandy Creek (Figure 18).

The topography of the area ranges from extreme relief in the Wind River Mountain Range, to relatively flat desert land along Big Sandy Creek. Elevations range from 6,300 feet at the confluence of the Green River and Big Sandy Creek, to more than 12,000 feet in the Wind River Mountains.

The headwaters areas of Big Sandy Creek and its tributaries are underlain by insoluble pre-Cambrian rocks of the Wind River Range. These peaks, which constitute a minor portion of the area, yield most of the runoff in Area 2. A minor portion of the runoff is derived from Green River Desert areas which are underlain by saline Tertiary lake bed materials. Effluent ground-water from the saline lake beds reaches Big Sandy Creek near its mouth.

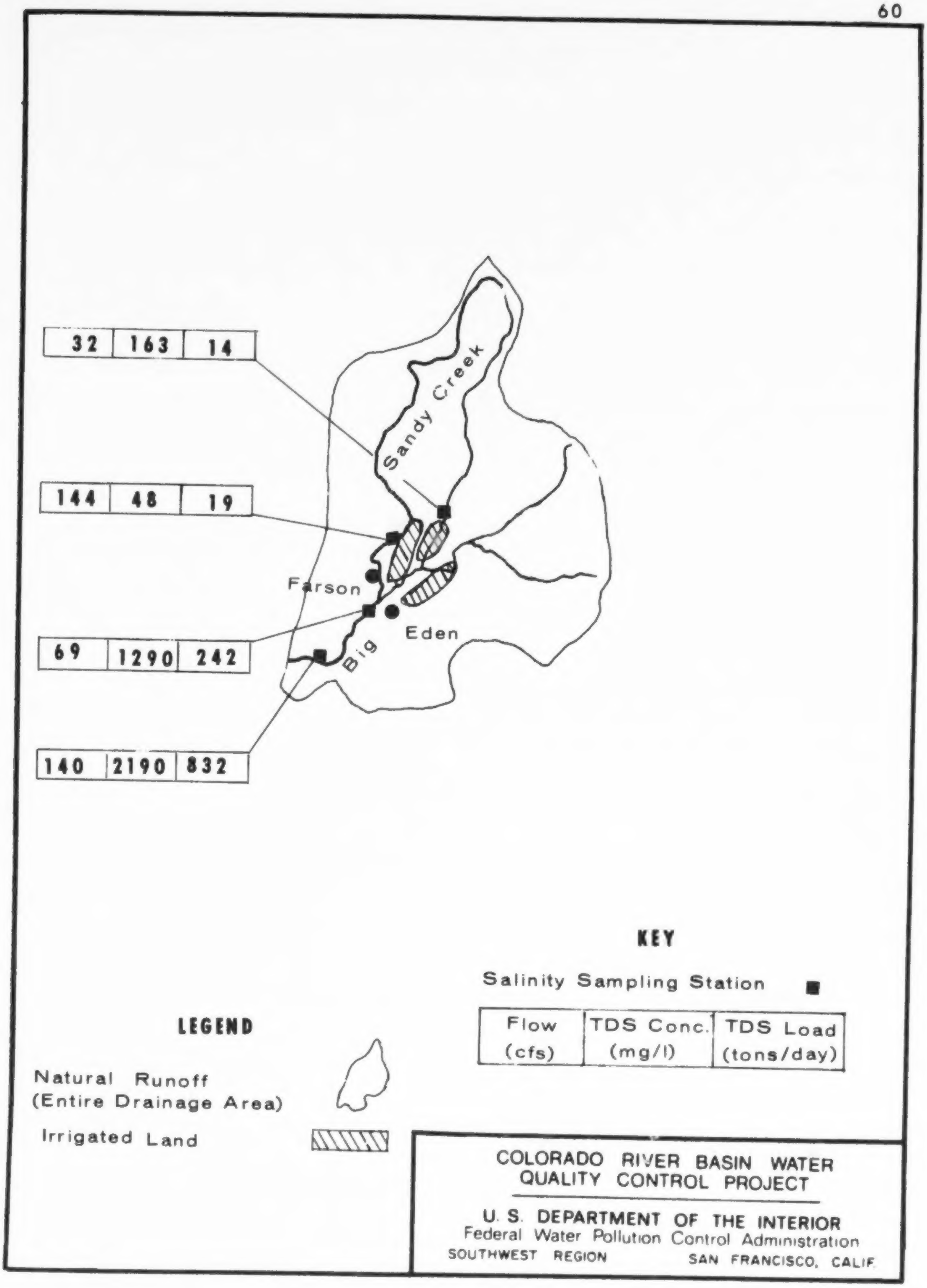
32 | 163 | 14
144 | 48 | 19
69 | 1290 | 242
140 | 2190 | 832
Sandy Creek
Farson
Eden
Big
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF.

Figure 18 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 2, Upper Colorado River Basin, 1965-66

Findings. During the study period, the headwaters streams located in insoluble outcrop areas yielded approximately 10 tons of salt per day. The irrigation of 13,000 acres contributed approximately 200 tons of salt per day, or an average of 5.6 tons per acre per year. The salt load yield from these irrigated areas was among the highest observed within the Basin, and results from leaching of the soluble gypsiferous sediments. Groundwater seepage from saline lake beds caused an increase in flow of 71 cfs and a salt load increase of 590 tons per day between the USGS gage below Eden, Wyoming, and the mouth of Big Sandy Creek.

The chemical composition changed from essentially pure water in the headwaters areas to predominantly sulfate-type water at the sampling station below Eden, Wyoming. All cations increased above the Eden station, and sodium became predominant in the reach below Eden. Chemical composition of Big Sandy Creek, at its mouth, was essentially identical to that of seepage collected in the stream reach below Eden. The high sulfate content of the seepage water is caused by solution of gypsum underlying the area.

The salt budget for Area 2 is shown in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Irrigation	200	24
Runoff	632	76
Total	832	

Study Area 3 (Green River Subbasin)

Description. Area 3 comprises the Green River drainage area between Big Sandy Creek and Blacks Fork River, which covers approximately 2,960 square miles in Sweetwater County in Wyoming (Figure 19). Rock Springs

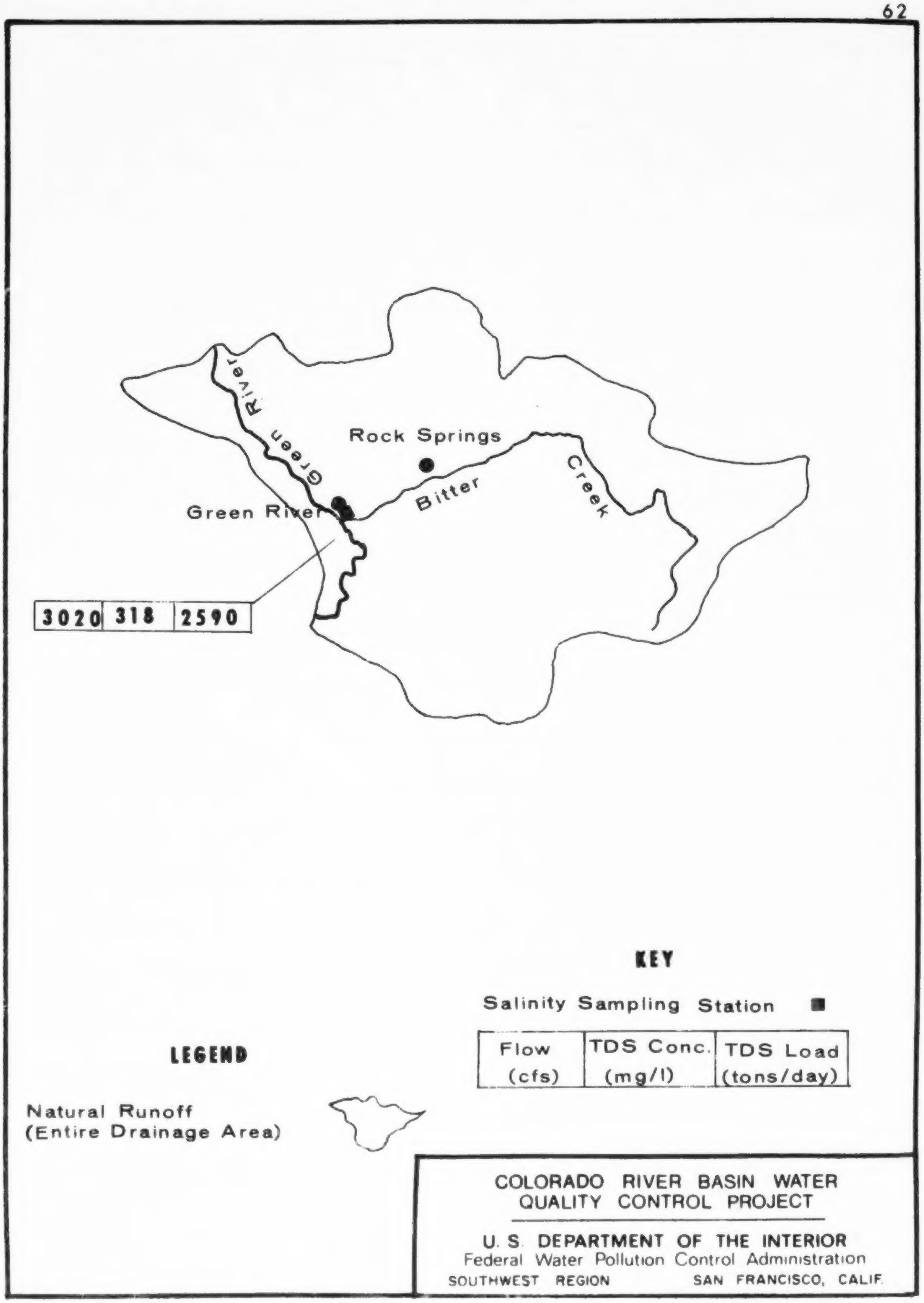
Green River
Rock Springs
Green River
Bitter Creek
3020
318
2590
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF.

Figure 19 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 3, Upper Colorado River Basin, 1965–66

and Green River, with 1960 populations of 10,371 and 3,496, respectively, are the only significant communities in the area. Bitter Creek is the only significant tributary to the Green River within Area 3. The Bitter Creek drainage area is underlain by continental and marine rocks which are mostly shale and shaley sandstone of Cretaceous and Tertiary age. The Bitter Creek area receives very little precipitation and yields only small quantities of water except during periods of storms.

Findings. The increase of 360 cfs and 481 tons of salt per day from the tributary area between Fontenelle Dam and the mouth of Bitter Creek resulted from seepage of mineralized ground-water from highly saline rocks underlying the drainage area.

The flow and salt load contribution by Bitter Creek varied widely during the year. Flows ranged from 4 to 40 cfs and the salt load varied from 26 to 280 tons per day. Flow data were insufficient to permit calculation of a mean annual salt load contribution. It is estimated, based upon available data, that natural runoff from the highly saline geologic formations in the Bitter Creek watershed added a salt load of more than 30 tons per day to the area. Discharges from the communities of Rock Springs and Green River added a salt load of one ton per day.

The chemical composition diagram for the station near Green River, Wyoming, showed a significant increase in sulfate due to the saline inflow within the reach (Figure 48).

The salt budget for Area 3 is shown in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Municipal	1	0.3
Irrigation	30	8.6
Runoff	317	91.1
Total	348	

Study Area 4 (Green River Subbasin)

Description. Area 4 includes the entire Blacks Fork River drainage basin which covers 3,630 square miles in Lincoln, Uinta, and Sweetwater Counties in Wyoming; and Summit County in Utah (Figure 20). Kemmerer and Lyman, the only sizeable communities within the area, had populations of 2,028 and 425, respectively, in 1960.

Elevations of the area range from 6,000 to more than 10,000 feet. Annual precipitation isohyets roughly parallel the contours and range from less than 8 inches to more than 40 inches per year.

Principal tributaries to Blacks Fork River are Muddy Creek and Hams Fork River. Blacks Fork River heads high in the rugged, glaciated Uinta Mountains. Muddy Creek and Hams Fork River head in the Wyoming Mountains. Virtually all runoff in the area is derived from the Uinta Mountans which are underlain by insoluble igneous and metamorphic rock which yield water of excellent quality. Only a minor portion of the flow originates in the higher glacial moraine areas just north of the Utah-Wyoming line.

Findings. "Reagan Spring," located near Interstate 80 bridge over Muddy Creek contributed approximately 2 tons of salt per day.

Irrigation of 71,000 acres in the vicinity of Lyman, Mountainview, and Fort Bridger, contributed a salt load of 475 tons per day or an average of 2.4 tons per acre per year. This yield is significantly larger than the 0.9 tons of salt per acre per year reported by Iorns, et al. This disparity probably reflects leaching of new lands brought under irrigation since preparation of the Iorns report. Irrigation of 7,000 acres of hay and pasture lands upstream of Frontier, Wyoming, added a salt load of 6 tons per day to the system.

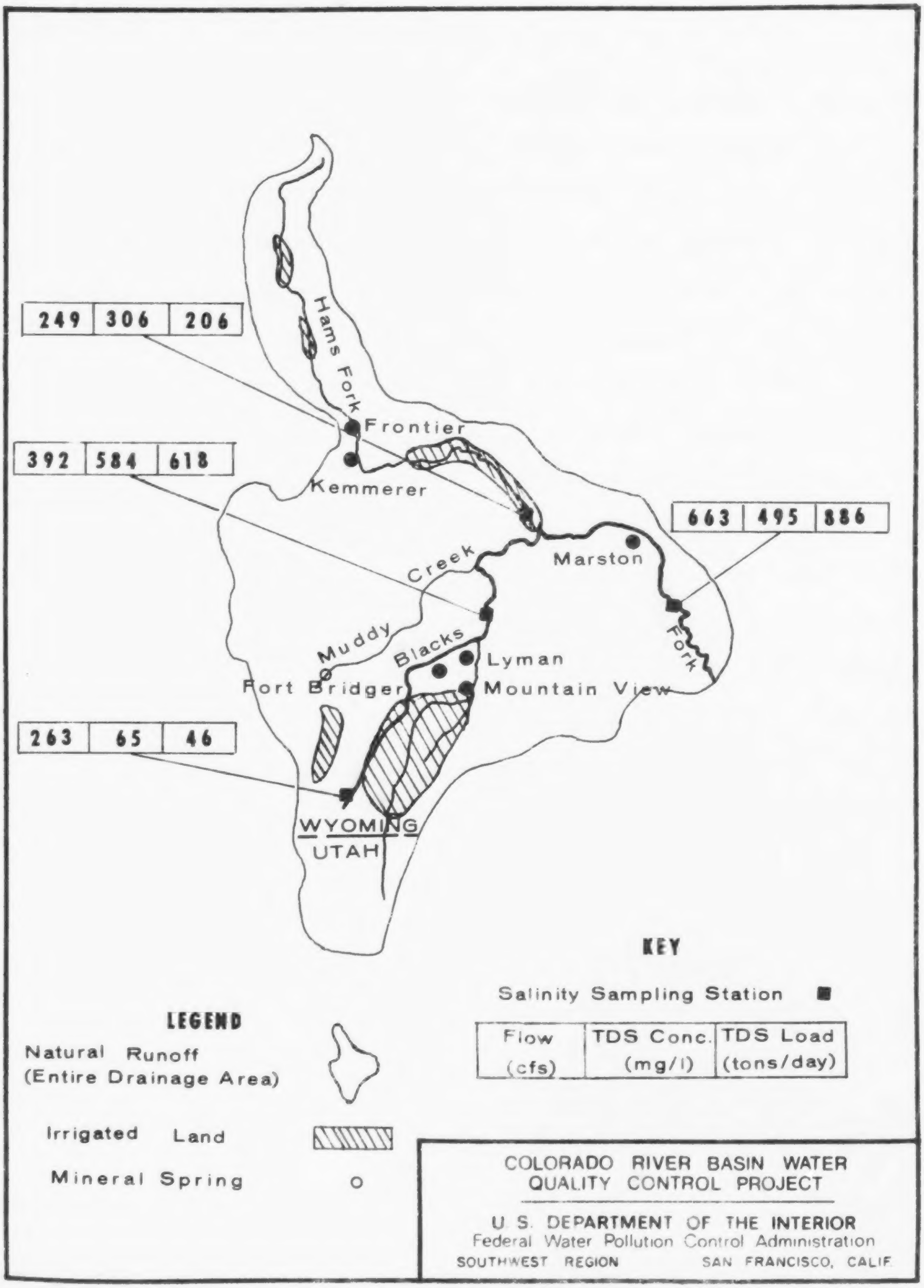
249 | 306 | 206
392 | 584 | 618
663 | 495 | 886
263 | 65 | 46
Hams Fork
Frontier
Kemmerer
Muddy Creek
Marston
Fork
Blacks
Lyman
Fort Bridger
Mountain View
WYOMING
UTAH
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land
Mineral Spring
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Figure 20 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 4, Upper Colorado River Basin, 1965–66

The salt budget for Area 4 is presented in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Irrigation	481	54.3
Springs	2	0.2
Runoff	403	45.5
Total	886	

Study Area 5 (Green River Subbasin)

Description. Area 5 includes the Green River drainage between the mouth of Blacks Fork River and the mouth of the Yampa River (Figure 21). It covers 3,555 square miles in Sweetwater County in Wyoming; Summit and Daggett Counties in Utah; and Moffat County in Colorado.

The headwaters of the area are located on the older sediments and igneous outcrops of the Uinta Mountains. This small area yields virtually all runoff within the study area. In Utah, the Green River crosses a small outcrop of sediments of Cretaceous through Mississippian age which yield good quality water. Downstream from Sheep Creek, the Green River crosses a fault and enters the canyon cut in pre-Cambrian meta-sediments of the Uinta Range which also yield high quality water. The sediments to the north and east of the Green River yield smaller amounts of water with higher concentrations of dissolved minerals.

Findings. The Uinta Mountains yield most of the runoff within Area 5. Runoff from these headwaters areas is of excellent quality. Small amounts of tributary inflow in the downstream areas contain variable amounts of minerals dissolved from the sedimentary formations. Irrigation of 18,000 acres of hay and pasture lands along Henrys Fork contributed a salt load of 243 tons per day or an average of 4.9 tons per acre

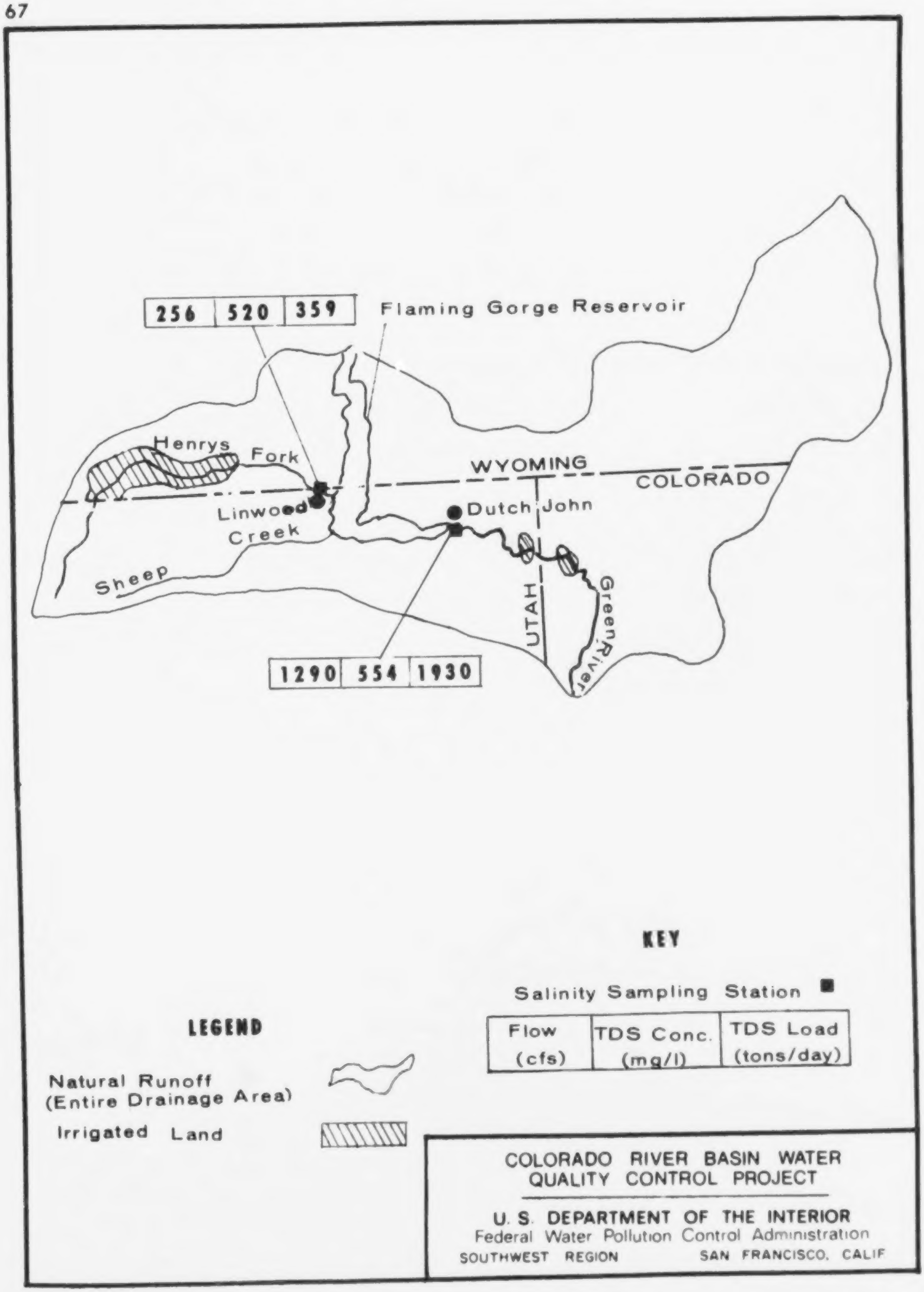
256
520
359
Flaming Gorge Reservoir
Henrys Fork
WYOMING
COLORADO
Linwood
Creek
Sheep
Dutch John
UTAH
Green River
1290
554
1930
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U. S. DEPARTMENT OF THE INTERIOR
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Figure 21 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 5. Upper Colorado River Basin, 1965–66

per year. This relatively large salt contribution is due to the leaching of the soluble sediments which underly most of the irrigated area.

Runoff added more than 2,300 tons per day to the total salt load from the area. Most of this load originates from the soluble sediments of the lower areas. During the study period, storage in Flaming Gorge Reservoir caused a negative salt load balance for Area 5.

Chemical composition of Henrys Fork at Linwood is predominated by calcium sulfate and with the exception of a low sodium content, is typical of Upper Basin streams which receive drainage from irrigated areas (Figure 48). Mineral composition of the Green River below inflows from Blacks Fork and Henrys Fork is typical of mature streams in the Basin, i.e., calcium and sodium are the predominant cations, and sulfate concentrations exceed those of bicarbonate and chloride.

The salt budget for Area 5 is shown in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Irrigation	243	9.4
Runoff	2337	90.6
Flaming Gorge Reservoir Storage	-3770	
Total	-1190	

Study Area 6 (Green River Subbasin)

Description. Area 6 includes the entire Yampa River drainage basin, and covers 3,560 square miles in Routt and Moffat Counties in Colorado; and Carbon and Sweetwater Counties in Wyoming (Figure 22). Principal communities within the area included Steamboat Springs, Hayden, Craig, and Maybell in Colorado; and Baggs in Wyoming.

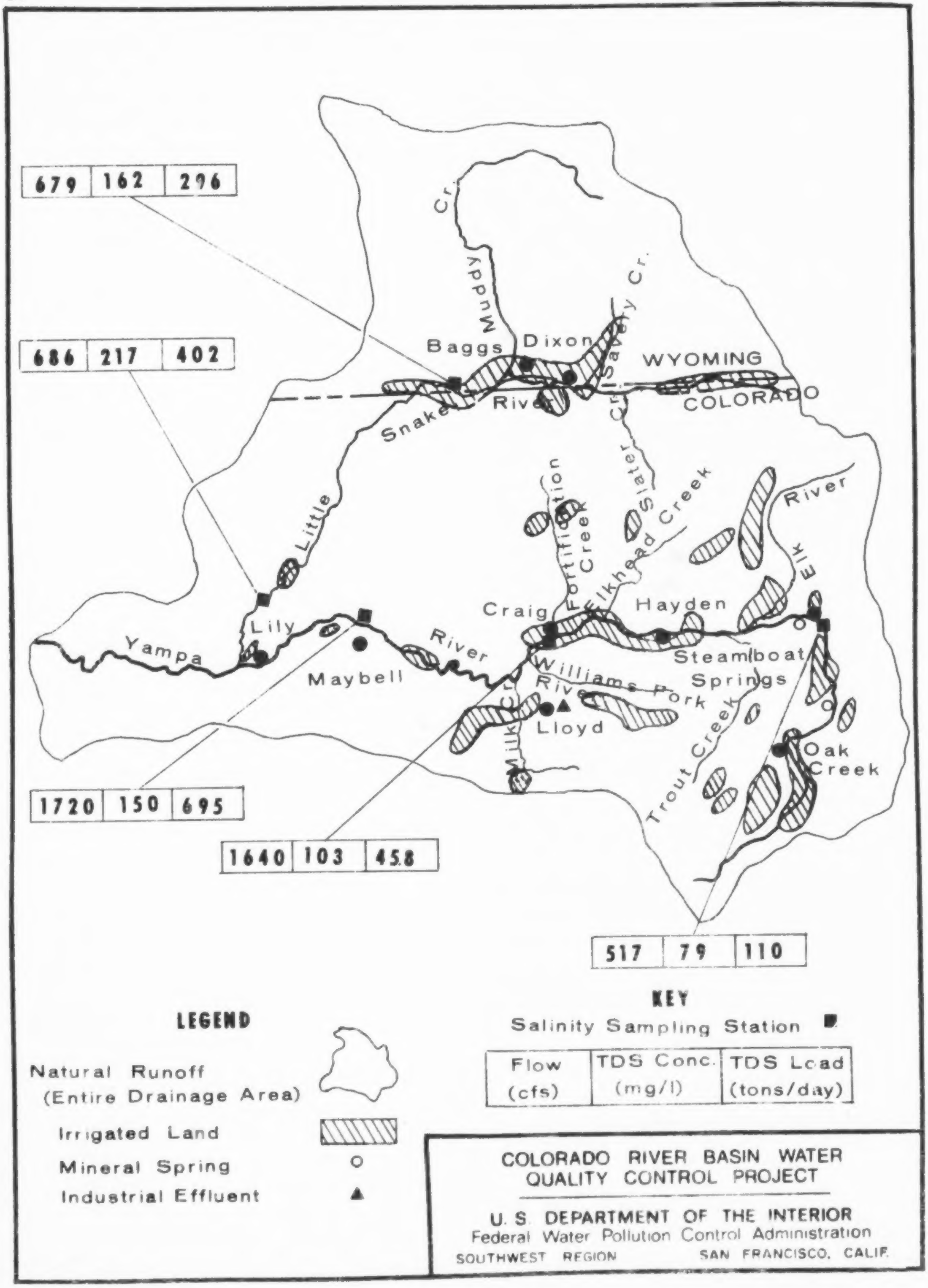
679 | 162 | 296
686 | 217 | 402
1720 | 150 | 695
1640 | 103 | 45.8
517 | 79 | 110
Muddy Cr.
Savery Cr.
Baggs
Dixon
WYOMING
COLORADO
Snake River
Little
Slater Cr.
Fortification Creek
Elkhead Creek
Elk River
Craig
Hayden
Lily
Yampa River
Maybell
Williams Fork River
Steamboat Springs
Milk Cr.
Lloyd
Trout Creek
Oak Creek
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land
Mineral Spring
Industrial Effluent
KEY
Salinity Sampling Station
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
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Figure 22 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 6, Upper Colorado River Basin. 1965–66

The Yampa River heads on flat-lying lava flows of the White River Plateau at elevations greater than 12,000 feet. Major tributaries upstream of Steamboat Springs head in mountains of the Park Range along the Continental Divide. These headwater areas are underlain by insoluble granitic rocks. Precipitation on these high areas exceeds 50 inches per year and runoff is of excellent quality. Downstream areas receive as little as 10 inches of precipitation per year. Runoff from these saline formations contains moderate concentrations of dissolved minerals.

Findings. The TDS concentrations in Yampa River near Oak Creek, Colorado, ranged from 177 mg/l to 329 mg/l during the study period. The concentrations in the Yampa River at Steamboat Springs ranged from 29 to 174 mg/l. This illustrates the effect of the high quality runoff from the Park Range which enters the Yampa above Steamboat Springs.

The total salt load of 110 tons per day in the Yampa River at Steamboat Springs includes approximately 6 tons per day from an abandoned coal mine located along Oak Creek just downstream of Oak Creek, Colorado. Mineral springs in the vicinity of Steamboat Springs add approximately 24 tons of salt per day. Irrigation of approximately 38,000 acres of forage land contributes 20 tons of salt per day or an average of 0.2 ton per acre per year.

The mean flow and salt load in the Yampa River at Craig, Colorado, was 1,643 cfs and 458 tons per day, respectively. This reflects an addition of 1,126 cfs and 324 tons of salt per day downstream of Steamboat Springs. Approximately 300 tons per day of this load is from natural runoff contributed by Elk River, Elkhead Creek, Trout Creek, Fortification

Creek, and other small streams. The remaining salt load addition of 24 tons per day results from irrigation along the Yampa River and its tributaries. The average salt yield from irrigation was approximately 0.4 tons per acre per year. This value is in close agreement with the findings of Iorns, et al.(4)

The Yampa River at Maybell carried a mean annual flow of 1,720 cfs and a mean salt load of 695 tons per day during the study period. This represents an increase of 78 cfs and 237 tons per day over the flow and salt load of the Yampa River at Craig. The release of saline water from the Iles Dome Oil Field located south of Lloyd, Colorado, was responsible for the addition of 4 cfs and 17 tons of salt per day. Inflow from Milk Creek added 96 tons of salt per.day and 30 cfs. Approximately 6 tons per day of this addition resulted from irrigation of 2,100 acres of forage area along Milk Creek. Natural runoff from Mancos shale outcrop areas contributed 90 tons of salt per day. The Williams Fork River yielded a salt load of 64 tons per day and a flow of 44 cfs. A Portion of this load resulted from spillage of brine produced in the Williams Fork Oil Field. Release of this saline water was discontinued during the study period. Irrigation of 16,000 acres along Williams Fork added an estimated 13 tons of salt per day to the system.

Observed changes in chemical composition of the Yampa River between Steamboat Springs and Maybell were insignificant (Figure 48). Although TDS concentrations decreased between Oak Creek and Steamboat Springs, the effect of the saline bedrock above Oak Creek is reflected by the increase in sodium concentration at Steamboat Springs.

The Little Snake River and Slater Fork one of its principle tributaries, yielded water with a TDS concentration of less than 160 mg/l throughout the year. This excellent quality water reflects the insoluble nature of the pre-Cambrian granite along the Continental Divide. Savery Creek, another tributary to the Little Snake River, discharged water with high salt concentrations derived from mineralized Tertiary sediments. Runoff per square mile from Savery Creek watershed was approximately equal to that for the Little Snake River; however, the salt contribution was about twice as great.

Approximately 15,000 acres of irrigated land above Dixon contributed 15 tons of salt per day or an average of 0.3 ton per acre per year to the Little Snake River. An additional 25 tons per day was added by irrigation of 17,000 acres along the Little Snake between Dixon and Baggs.

During the study period the Little Snake at Lily yielded a mean annual flow of 686 cfs and a salt load of 402 tons per day. The major portion of the salt load increase in Area 6 resulted from mineralized natural runoff and the solution of minerals from the bed and banks of the Little Snake River.

The salt budget for Area 6 is shown in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Springs	24	2.2
Irrigation	103	9.4
Industrial (Oil field produced water)[1/]	17	1.5
Mine Drainage	6	0.5
Runoff	950	86.4
Total	1100	

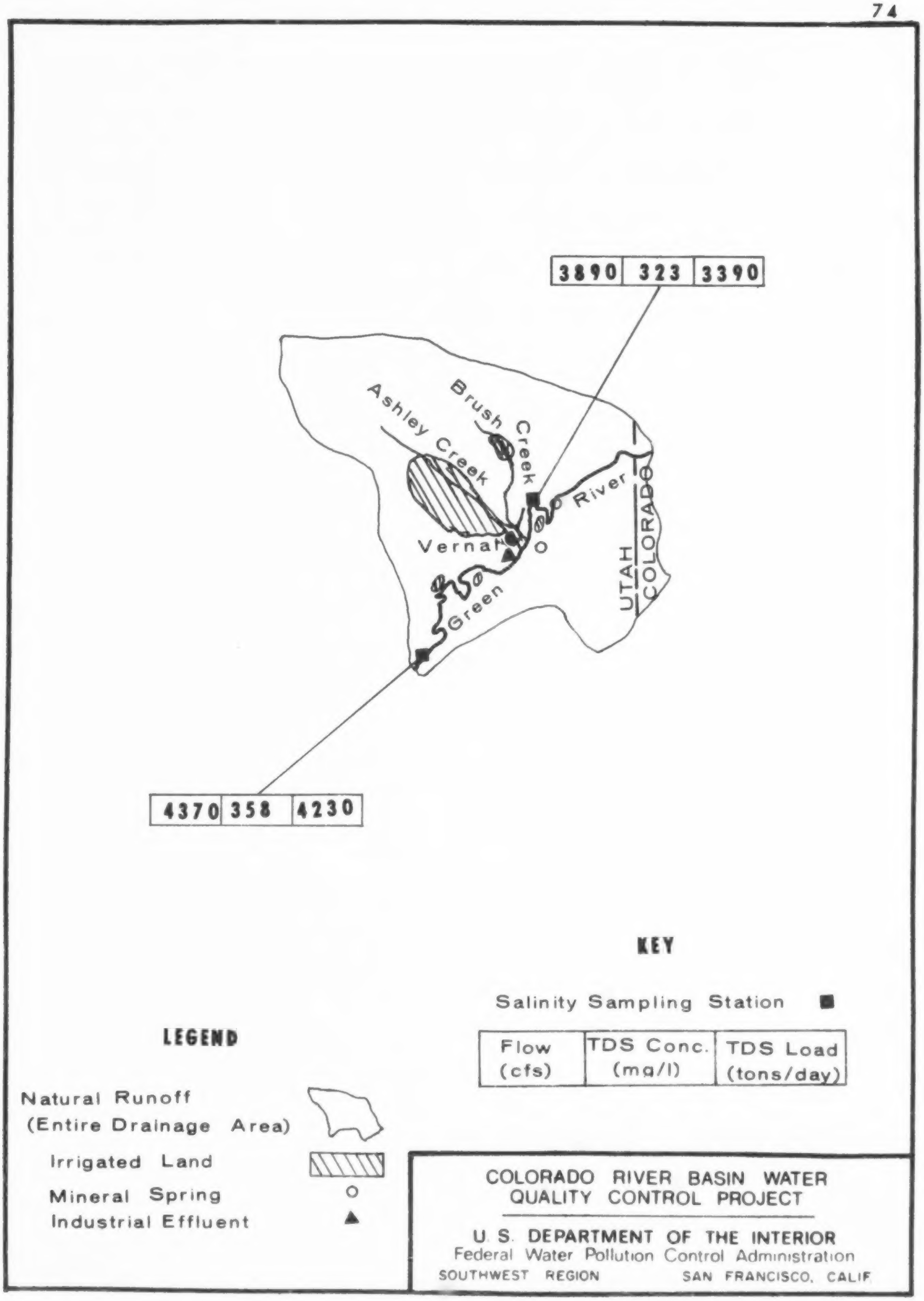
[1/] Does not include discharge of saline water from Williams Fork Oil Field which was discontinued during the study period.

Study Area 7 (Green River Subbasin)

Description. Area 7 includes the Green River watershed below the mouth of the Yampa River and above the mouth of the Duchesne and White Rivers. This 1,650 square mile area is located mostly within Uintah County of Utah but includes a small portion of Moffat County in Colorado (Figure 23). Major tributaries include Brush, Ashley, Cliff, and Jones Hole Creeks. Vernal, Utah, the only major community within the area, had a population of 3,655 in 1960.

Brush and Ashley Creeks originate high in the rugged, glaciated Uinta Mountains. The Jones Hole Creek drainage area consists of high uplands with deeply incised stream channels and steep hogbacks. The streams flow southward to the Uinta Basin, a plateau underlain by flat-lying sediments of Tertiary through Quaternary Ages. Elevations of the area range from less than 4,800 feet to more than 10,000 feet. Annual precipitation isohyets closely follow elevation contours and ranges from less than 8 inches per year on the lowlands to more than 40 inches per year on the Uinta peaks. Thus, most of the runoff in Area 7 is derived from a relatively small area of pre-Cambrian rock formation and is relatively free of dissolved minerals. The sediments of lower areas yield smaller quantities of salt-laden water.

Findings. Data from survey stations on Brush Creek and Little Brush Creek indicated that large losses of water occurred during the irrigation season, and smaller losses occurred during the base flow period. Salt loss occurred throughout the period of study indicating that salt may have been stored in some portions of the 5,100 acres of irrigated land within the area.



3890 | 323 | 3390
Brush Creek
Ashley Creek
River
Vernal
Green
UTAH
COLORADO
4370 | 358 | 4230
KEY
Salinity Sampling Station
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land
Mineral Spring
Industrial Effluent
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Figure 23 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 7, Upper Colorado River Basin, 1965–66

The predominantly clacium-bicarbonate composition of Brush Creek during runoff months was characteristic of headwater streams in the Upper Basin. Large increases in mineral concentrations occurred during the irrigation season with sulfate being the prevalent anion. During the winter months, sodium and sulfate decreased, although sulfate remained the predominate anion. The high sulfate concentrations resulted from solution of gypsum by overland runoff and irrigation waters.

Water quality data on Ashley Creek watershed developed by the Bureau of Reclamation for the period 1957-1965 were included in the study. During water years 1959, 1960, and 1961, irrigation of 20,000 acres in Ashley Valley contributed approximately 50 tons of salt per day to Ashley Creek. In water year 1962 the salt load increased to more than 100 tons per day. In 1963, the salt load was only 60 tons per day and declined to approximately 30 tons per day for water year 1964. In water year 1965 the salt load was 100 tons per day. The salt load during the Project study period, June 1965 to May 1966, was computed to be approximately 230 tons per day, or an average of 4.2 tons per acre. The heavy snow pack in 1965 produced abundant runoff and local irrigators applied large amounts of water which undoubtedly leached out salts which had accumulated in the soils during the previous dry years.

Several salt springs and other sources of saline ground-water added to the salt load of the Green River in Area 7. Split Mountain Warm Springs, located in Dinosaur National Monument, are reported to contribute 51 tons of salt per day. These Springs have been inaccessible since the impoundment of Flaming Gorge Reservoir.

Water produced at the Ashley Valley Oil Field along the lower reaches of Ashley Creek is released to Ashley Creek for irrigation use. The water from the oil field contributed 32 tons of salt per day to the system. An oil-test hole located adjacent to U. S. Highway 40, east of Jensen, Utah, discharges 100 gallons per minute with a TDS concentration of 1,800 mg/1. This water is used for stock watering and was not included in the area budget.

Magnesium and sulfate ions increase in proportion to the other principal ions in the Green River as a result of irrigation return flows (Figure 48).

The salt budget for Area 7 is shown in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Springs	51	5.6
Irrigation	230	25.2
Industrial	32	3.5
Runoff	599	65.7
Total	912	

Study Area 8 (Green River Subbasin)

Description. Area 8 consists of the entire Duchesne River drainage basin, comprising 3,820 square miles located mostly in Duchesne County but including small portions of Uintah and Wasatch Counties in Utah (Figure 24).

Most of the streams originate in the glaciated Uinta Mountains or the high uplands of the Wasatch Plateau. The Uinta Mountains are underlain by crystalline rocks which yield runoff of excellent quality. The Wasatch Plateau is a high rolling upland with deeply incised streams. The area is underlain by marls, shales, and oil shales of the Green River

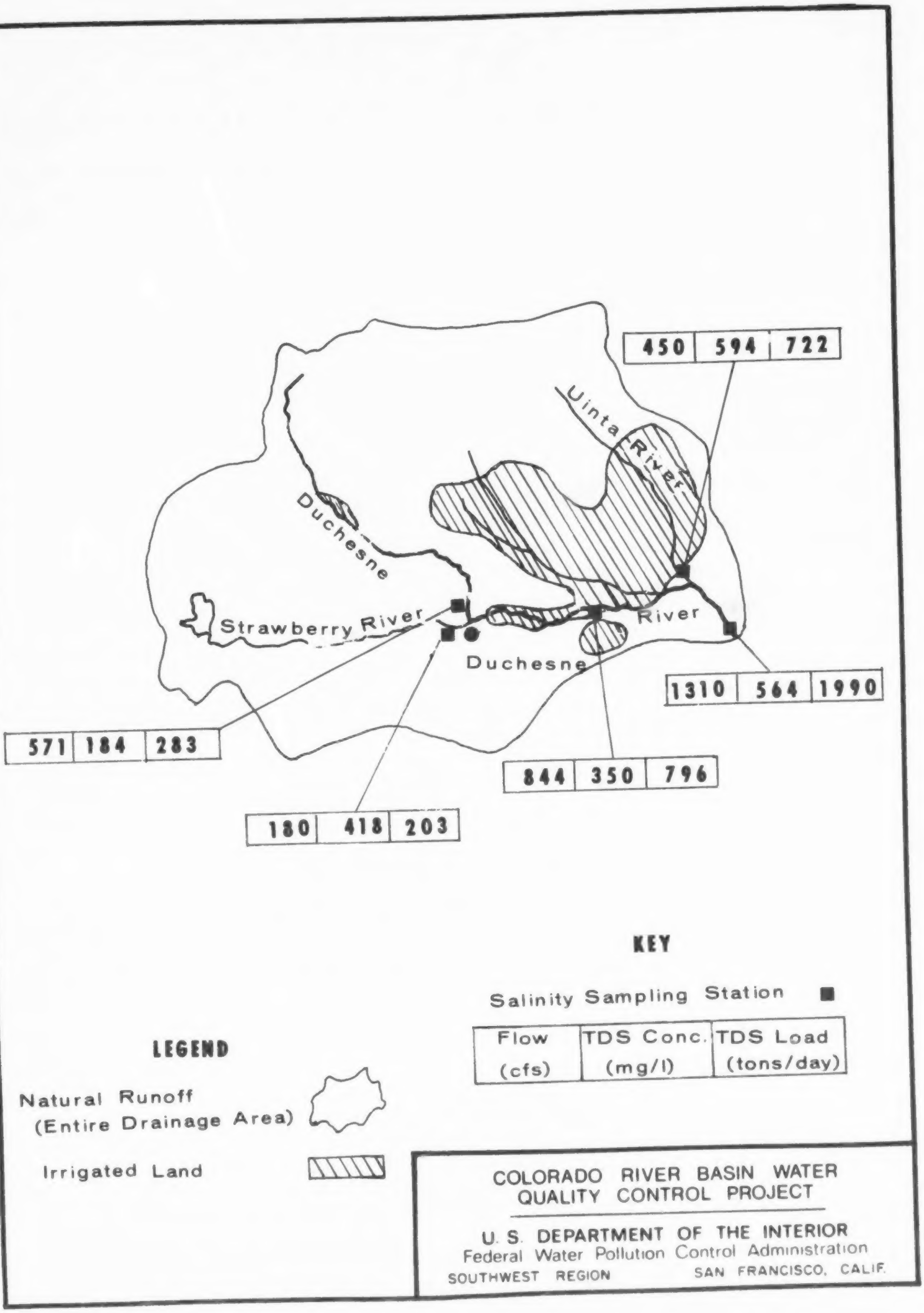
450 | 594 | 722
Uinta River
Duchesne
Strawberry River
River
Duchesne
1310 | 564 | 1990
571 | 184 | 283
844 | 350 | 796
180 | 418 | 203
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land ▨
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Figure 24 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 8, Upper Colorado River Basin, 1965–66

and Uinta formations which contain numerous soluble minerals. The streams flow south to the Uinta Basin crossing sedimentary layers en route. The valley floor, which covers the greater part of the study area, is underlain with flat-lying Tertiary rock.

Virtually all the runoff in Area 8 is derived from the south flanks of the Uinta Mountains or from headwaters area of the Strawberry River. Together, these areas make up less than 10 percent of Study Area 8.

Findings. Several discrete natural sources discharge minor salt loads to streams within the area. Stinking Springs on the Strawberry River discharges from 20 to 50 gallons per minute of water with a TDS concentration of approximately 7,700 mg/l. These Springs contribute a salt load of approximately 1.3 tons per day. Springs along Indian Creek add 3.3 tons of salt per day to the system.

The 166,000 acres of irrigated land in Area 8 adds approximately 1,350 tons of salt per day to the system. This amounts to an average yield of 3.0 tons per acre per year.

Ionic composition of the headwaters of the Duchesne River was of the characteristic calcium-bicarbonate type (Figure 48). Inflow of poor quality water from the Strawberry River caused increases in the proportions of sodium and sulfate. The composition diagram for the most downstream station on the Duchesne showed the calcium, sodium, sulfate pattern characteristics of a mature stream carrying irrigation return water.

The salt budget for Area 8 is given in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Springs	4	0.2
Irrigation	1350	67.8
Runoff	636	32.0
Total	1990	

Study Area 9 (Green River Subbasin)

Description. Area 9 includes the entire drainage area of the White River and covers approximately 44,000 square miles in Garfield, Rio Blanco, and Moffitt Counties of Colorado; and Uintah County in Utah (Figure 25). The area includes the communities of Meeker and Rangely, and several other smaller settlements. The area has a total population of approximately 5,600.

Main tributaries of the White River include the South Fork of the White River and Piceance, Yellow, Douglas, and Evacuation Creeks. The White River and South Fork of the White River originate on the White River Plateau at elevations over 12,000 feet. This Plateau consists of a series of flat lava flows with glaciated valleys through which the headwater streams flow. Runoff from this Plateau is of good quality. Below Meeker, the river channel cuts through the Grand Hogback and then enters more varied topography consisting of plateaus, ridges, and cliffs, interspersed with open valleys. The varied topography reflects the varying erosion resistence of the rocks which underlie the area. The easily eroded formations in the lower elevations yield small amounts of mineralized water.

Findings. During the study period, the White River at Buford discharged a mean flow of 352 cfs and a mean salt load of 157 tons per day. The South Fork of the White River at Buford yielded a mean flow of 310 cfs and a mean salt load of 115 tons per day. These two streams which originate on the White River Plateau contributed more than two-thirds of the total runoff, but less than one-fourth of the salt load from Area 9.

An increase of 30 cfs and 70 tons of salt per day was measured downstream at the Coal Creek station. Almost all of the increase in flow and

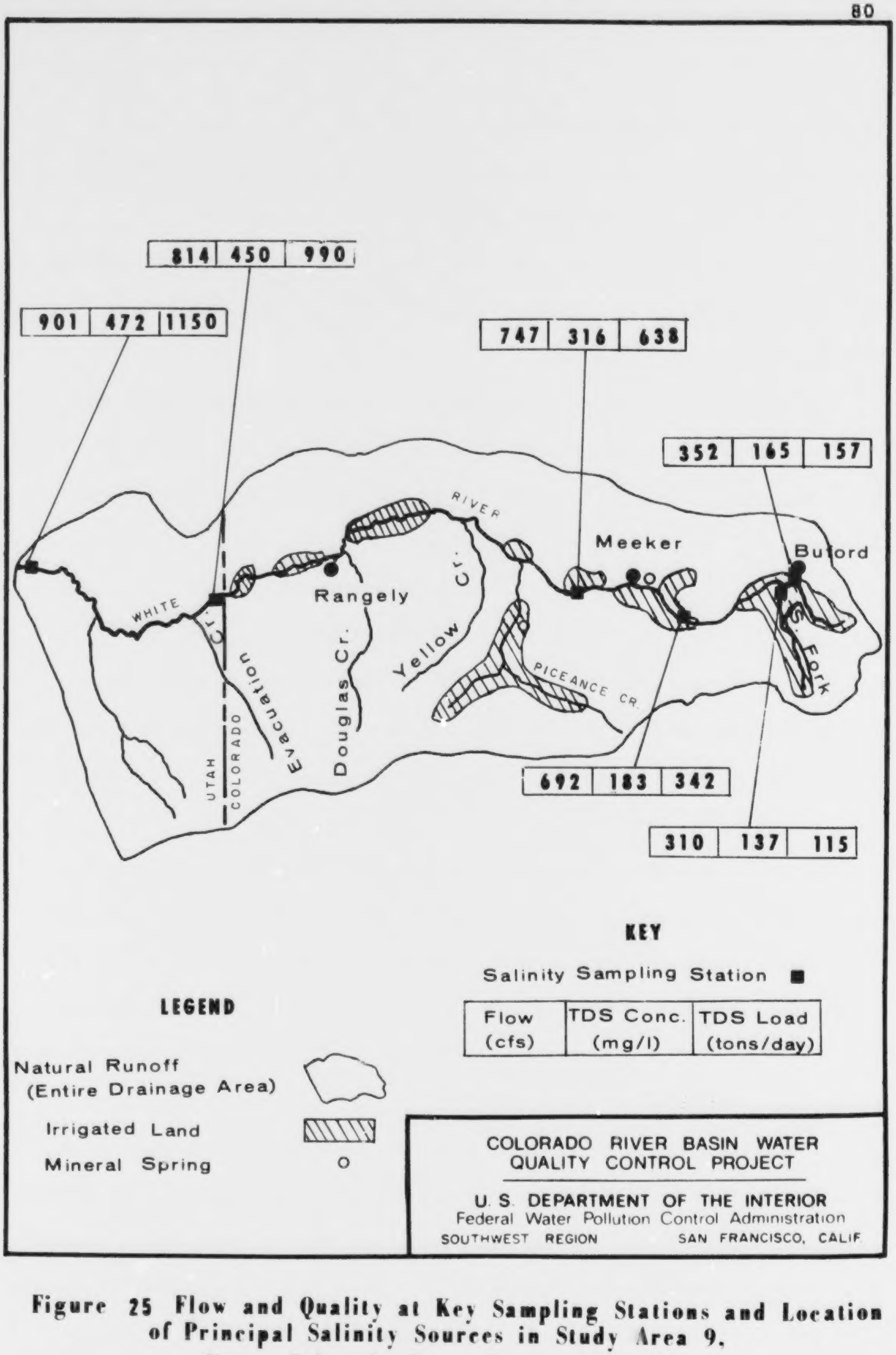
814 | 450 | 990
901 | 472 | 1150
747 | 316 | 638
352 | 165 | 157
692 | 183 | 342
310 | 137 | 115
WHITE
RIVER
Meeker
Buford
Rangely
Evacuation Cr.
Douglas Cr.
Yellow Cr.
PICEANCE CR.
S. Fork
UTAH
COLORADO
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land ▨
Mineral Spring ○
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
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Figure 25 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 9, Upper Colorado River Basin, 1965–66

salt load resulted from tributary inflow to the reach. The effect on water quality, of irrigation of approximately 10,000 acres within the White River reach between Buford and Coal Creek, was virtually nil. Soils within this reach have been well leached by abundant precipitation. No significant changes in chemical composition were observed between the Buford and Coal Creek stations.

Increases of 55 cfs and 296 tons of salt per day occurred between the Coal Creek and Meeker stations on the White River. An abandoned oil-test hole near Meeker contributed 3.1 cfs of water with a dissolved solids concentration of approximately 19,000 mg/l. This accounted for approximately 160 tons per day of the salt load increase within this reach. The remaining flow of 52 cfs and a salt load of 136 tons per day within the reach was from undefined sources. Irrigation of approximately 10,000 acres within the same reach yields an undetermined quantity of salt to the stream, but it is believed to be considerably less than the 136 tons per day from undefined sources.

In the past, water flowed from a test hole located on the mesa to the north of the White River. Salt water also flowed from a seismic shot hole until it was recently plugged. Thus, it is evident that saline water in the near surface formations east of Meeker is under artisian pressure and may be moving into the stream through naturally occurring fissures or other test holes.

Chemical composition changes in the White River reach between Coal Creek and Meeker tends to substantiate that salt load increases are caused by ground-water inflow. Sodium, chloride, and sulfate were the predominate ions in discharge from the Meeker oil-test hole. These ions increased markedly in the immediate reach of the White River.

Flow and salt load at the USGS station on the White River at Watson reflect an increase of 67 cfs and 352 tons of salt per day in the reach of the stream below Meeker. Approximately 100 tons per day of this increase is discharged from the Piceance Creek drainage area. This includes the salt contribution from irrigation of approximately 5,000 acres along Piceance Creek. A flowing oil-test hole along Piceance Creek added 17 tons of salt per day.

The salt load from Yellow Creek was approximately 7 tons per day. This included approximately 2 tons of salt per day from a sulfur spring located above the mouth of Yellow Creek. The TDS concentration in Yellow Creek exceeded 2,000 mg/l throughout the year. The salt load from Douglas Creek varied widely with flow, but was estimated to average 35 tons per day. Approximately 20 tons of salt per day were added by irrigation of small areas along the White River below Meeker.

The saline inflow from Piceance, Yellow, and Douglas Creeks caused major changes in chemical composition of the White River (Figure 48). Sodium, sulfate, and bicarbonate increased significantly below the entrance of these streams. Relatively small changes in salt loads and chemical composition were observed in the White River between Watson and Ouray, Utah.

The salt budget for Area 9 is given in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Irrigation	20[1/]	1.7
Abandoned oil-test holes	177	15.4
Springs	2	0.2
Runoff	951[1/]	82.7
Total	1150	

[1/] Includes salt contribution from irrigated areas along Piceance, Yellow, and Douglas Creeks.

Study Area 10 (Green River Subbasin)

Description. Area 10 includes the Green River drainage area between the mouth of the White River and the town of Green River, Utah (Figure 26). The area covers approximately 3,000 square miles in Grand, Emery, Carbon, Uintah, and Duchesne Counties of Utah. Major tributaries in the area include Willow Creek, Pariette Draw, Nine-Mile Creek (Minnie Maud Creek), and the Price River. There are no communities and few inhabitants within the area.

The Green River flows from the Uinta Basin toward the east side of the San Rafael Swell, cutting through the Roan Cliffs and Book Cliffs in Desolation Canyon. In the Uinta Basin, the rocks are flat lying and form broad flat valleys and mesas. In the Desolation Canyon area, streams are deeply incised with small flat mesas remaining. As the river flows south, it crosses progressively older rocks from the Tertiary sediments in the Ouray, Utah, area to the Mancos shale at Green River, Utah. The Book Cliffs are formed by the late Cretacious Mesa Verde group and Roan Cliffs are formed by the oil shales of the Green River formation. Runoff from all formations within the area is moderately to highly mineralized. The mean annual runoff from Area 10 is negligible except during snowmelt and infrequent summer storms.

Findings. During the study period, total flow within the area decreased by 66 cfs while the salt load increased by 510 tons per day. The total salt load added by Pariette Draw, Willow Creek and Nine-Mile Creek accounted for more than half of the salt load increase within the reach. The remaining increase was derived from minor tributaries and from direct runoff to the Green River. Virtually the entire salt load from Area 10 was attributable to natural runoff.

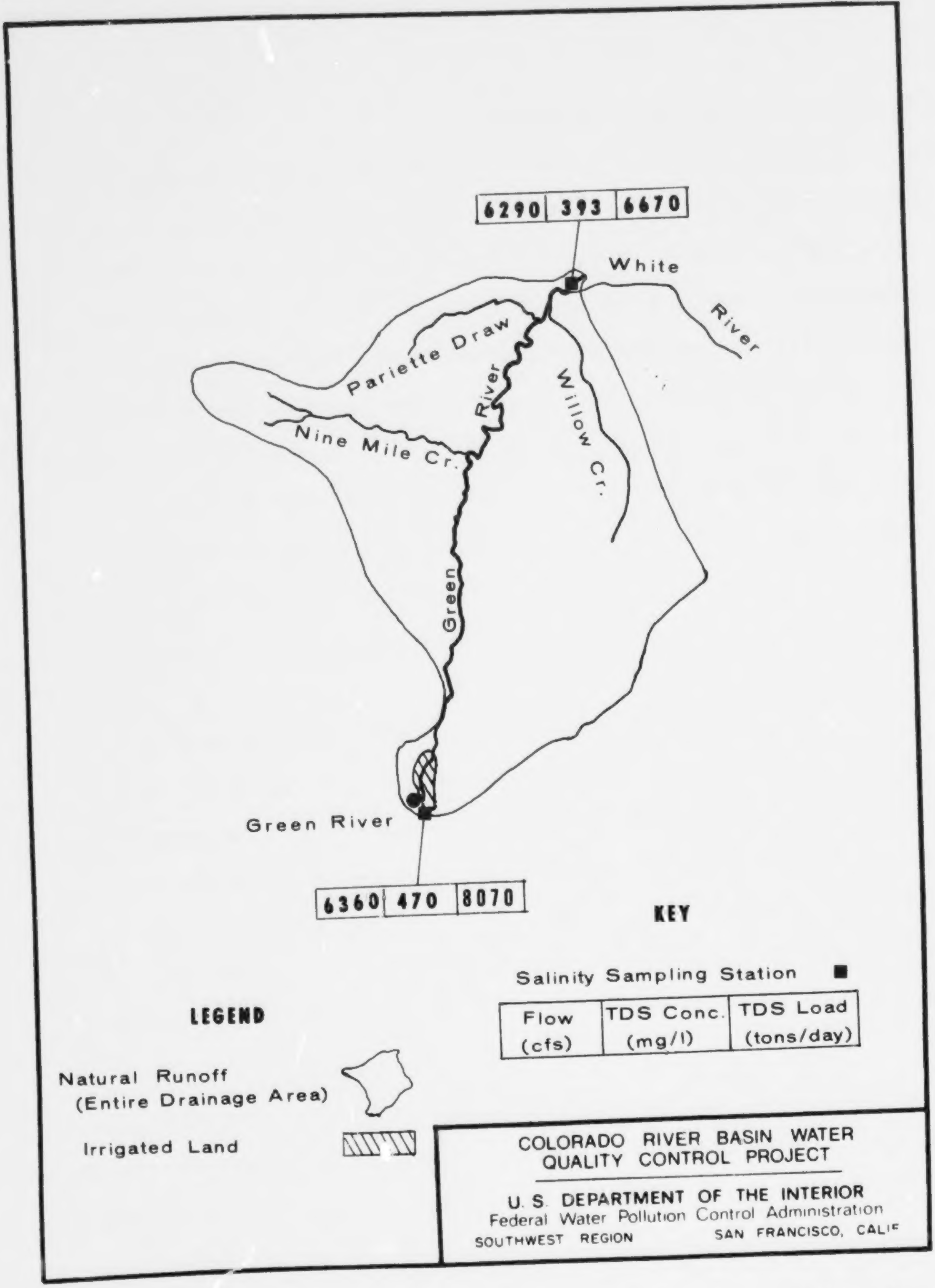

6290 | 393 | 6670
White
River
Pariette Draw
River
Willow Cr.
Nine Mile Cr.
Green
Green River
6360 | 470 | 8070
KEY
Salinity Sampling Station ■
Flow (cfs) | TDS Conc. (mg/l) | TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CAL

Figure 26 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 10, Upper Colorado River Basin, 1965–66

Study Area 11 (Green River Subbasin)

Description. Area 11 includes the entire Price River drainage basin, which covers approximately 1,900 square miles in western Carbon and northern Emery Counties of Utah, and small portions of adjacent counties. The communities of Castle Gate, Helper, Price, Wellington, Draggerton, and numerous smaller settlements are located in the area. (Figure 27)

Most of the runoff in the area originates along the east flank of the Wasatch Plateau, which forms the western boundary of the area. The Price River crosses the Book Cliffs, flows across Castle Valley, the source of most of the salt load in the Price River, then across the San Rafael Swell and across the Book Cliffs again, to join the Green River. The area downstream of Castle Valley yields little flow or salt, except during snowmelt or summer storms.

Findings. During the study period, the Price River at Woodside, Utah, carried a mean flow of 136 cfs and a mean salt load of 885 tons per day. Irrigation in the San Rafael River area contributed approximately 100 tons of salt per day. Runoff above the diversion dam near Price, Utah, yielded approximately 100 tons of salt per day. A coal washing plant[1/] and a dry ice manufacturing plant on Flood Wash near Wellington yielded 13 tons of salt per day. Municipal discharges added 3 tons of salt per day. The small tributaries and direct runoff below Price contributed approximately 80 tons of salt per day. The total measured salt load from Area 11 was approximately 300 tons per day leaving some 580 tons per day attributable to influent ground-water and irrigation.

[1/] The coal washing plant ceased operations subsequent to completion of this study.

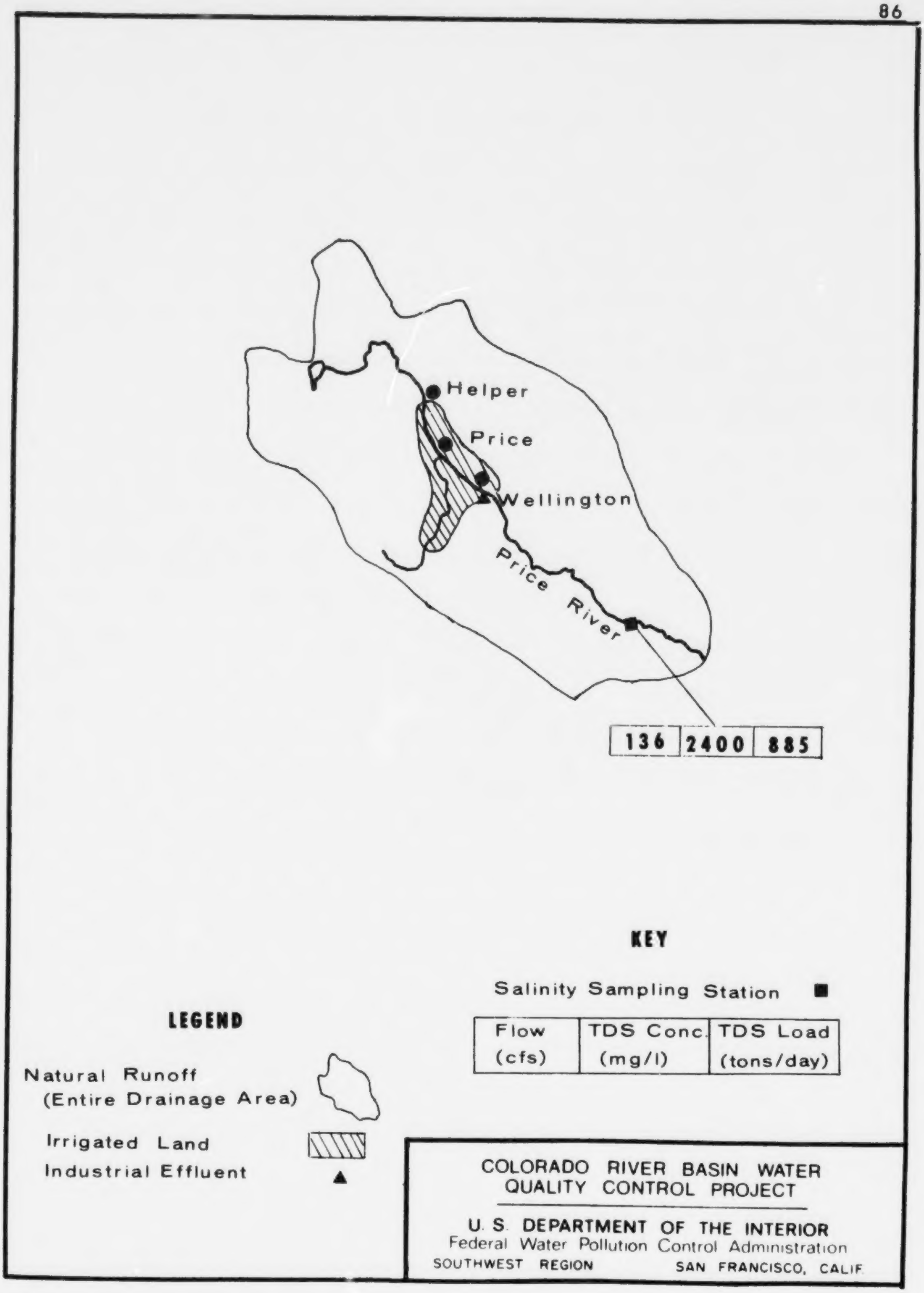

Helper
Price
Wellington
Price River
136
2400
885
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land
Industrial Effluent ▲
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF.

Figure 27 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 11, Upper Colorado River Basin, 1965–66

Very intensive study of ground-water conditions would be required to define the relative amounts of salt contributed by naturally occurring effluent ground-water and irrigation. If most of the unmeasured salt load was due to irrigation of the 25,000 acres in Castle Valley, the average yield would be on the order of 8.5 tons per acre per year. In any event, the application of irrigation water on the outcrop of Mancos shale severely degrades mineral quality of the Price River.

The effect of leaching of soils underlain by Mancos shale is reflected in the composition pattern diagram for the Price River at Woodside (Figure 48). The TDS concentration was very high with sulfate being the predominate anion. Concentrations of all cations were high, with sodium exceeding all others. Although discharge from the Price River is small compared to flow in the Green River, concentrations of sulfate and sodium in the Price River were sufficiently high to cause significant alteration in the chemical composition of the Green River.

The salt budget for Area 11 is shown in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Irrigation (Castle Valley)	580[1/]	65.5
Irrigation (San Rafael River)	100	11.3
Industrial	13	1.5
Municipal	3	0.3
Runoff	189	21.4
Total	885	

[1/] Includes effluent ground-water which cannot be quantified without extensive ground-water study.

Study Area 12 (Green River Subbasin)

Description. The study area is the San Rafael River drainage basin, including approximately 2,065 square miles in Emery and Sanpete Counties of Utah. There are no communities of sufficient size to have significant effect on mineral quality of water within the area. Rainfall within the area ranges from less than 8 inches per year at the lower altitudes to more than 40 inches per year in the higher altitudes. Virtually all the runoff from Area 12 is derived from streams which head in the uplands of the Wasatch Plateau, along the western edge of the study area. The streams then flow into the relatively flat Castle Valley which is underlain by the highly soluble Mancos shale. Most of the headwater streams are intercepted by the San Rafael River in the Castle Valley area. The San Rafael River crosses the San Rafael Swell which is underlain by sediments of the Morrison formation of the San Rafael group. These formations include thick beds of gypsum, but yield small amounts of runoff except during periods of snowmelt. The San Rafael River then crosses the relatively flat San Rafael desert and joins the Green River below Green River, Utah. The San Rafael watershed downstream of Castle Valley Yields relatively small amounts of runoff and salt due to the low annual precipitation. (Figure 28)

Findings. Two minor sources, Iron Wash Spring and Buckhorn Wash Spring contributed approximately 0.5 ton of salt per day to the stream system.

The Bureau of Reclamation collected extensive data on water quality in the Castle Valley area during the period 1962-1965. These data were

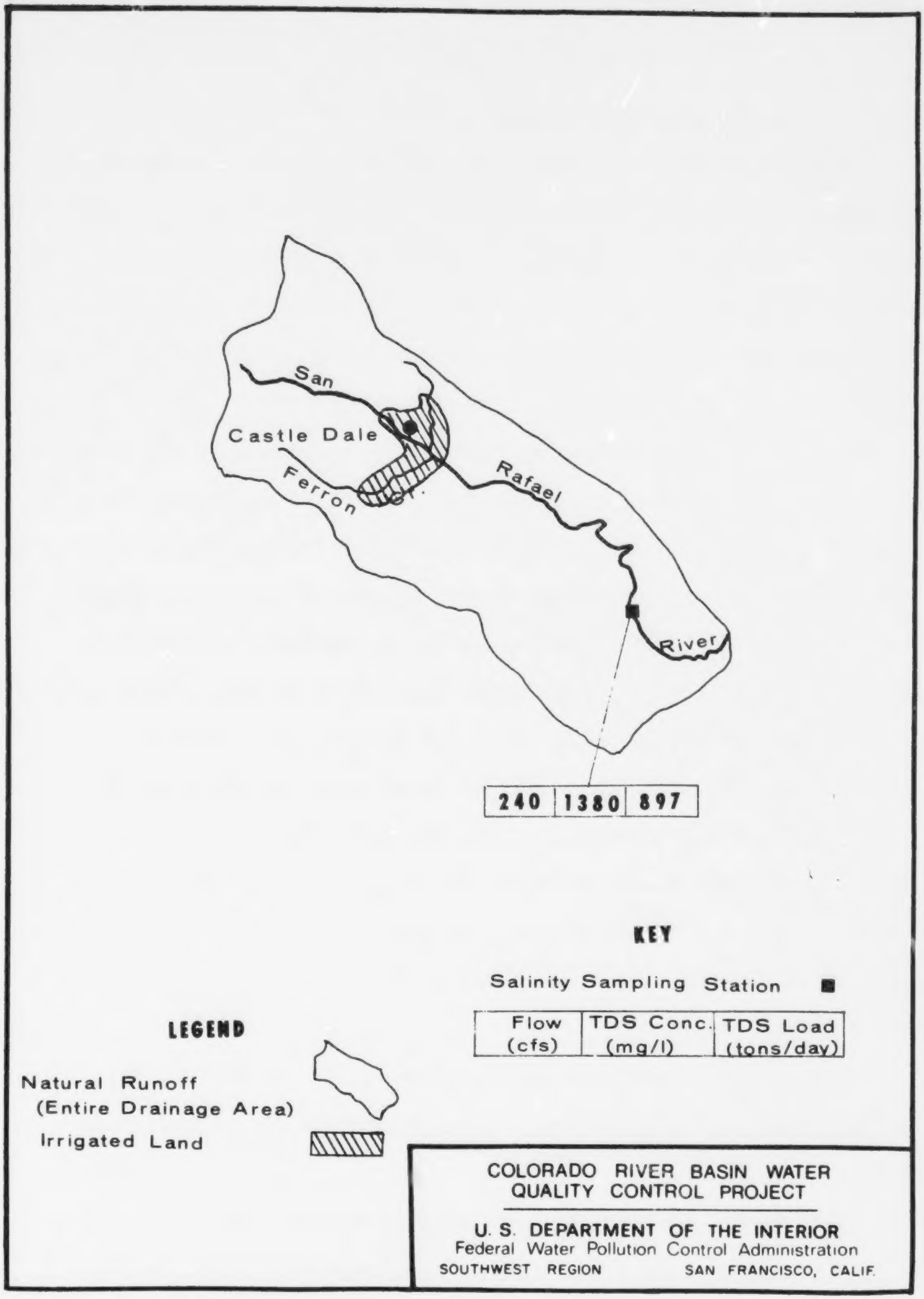

San
Castle Dale
Rafael
Ferron
Cr.
River
240
1380
897
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land ▨
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF.

Figure 28 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 12, Upper Colorado River Basin, 1965–66

combined with quality data collected by the Project in developing the salt budget for the area. Irrigation of 36,000 acres in Castle Valley added a salt load of approximately 290 tons per day, a portion of which is returned to the Price River. The average yield of approximately 2.9 tons per acre per year closely approximates the 3.2 tons per acre per year calculated by Iorns and his associates.(4) Runoff, the major salinity source in the area, increased the salt load from the area by 607 tons per day.

Chemical composition of the San Rafael River is similar to that of the Price River with sulfate being the major anion (Figure 48). Nearly equal amounts of calcium, magnesium, and sodium indicate that solution of gypsum from Mancos shale, by precipitation and applied irrigation water, is responsible for a major portion of the salt load input from this area.

The salt budget for Area 12 is shown in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Springs	<1	0.1
Irrigation	290	32.3
Runoff	606	67.6
Total	897	

Study Area 13 (Green River Subbasin)

Description. Area 13 consists of the Green River drainage below the town of Green River, Utah, exclusive of the San Rafael River drainage area (Figure 29). It covers approximately 1,900 square miles in parts of San Juan, Wayne, Grand, and Emery Counties in Utah. The community

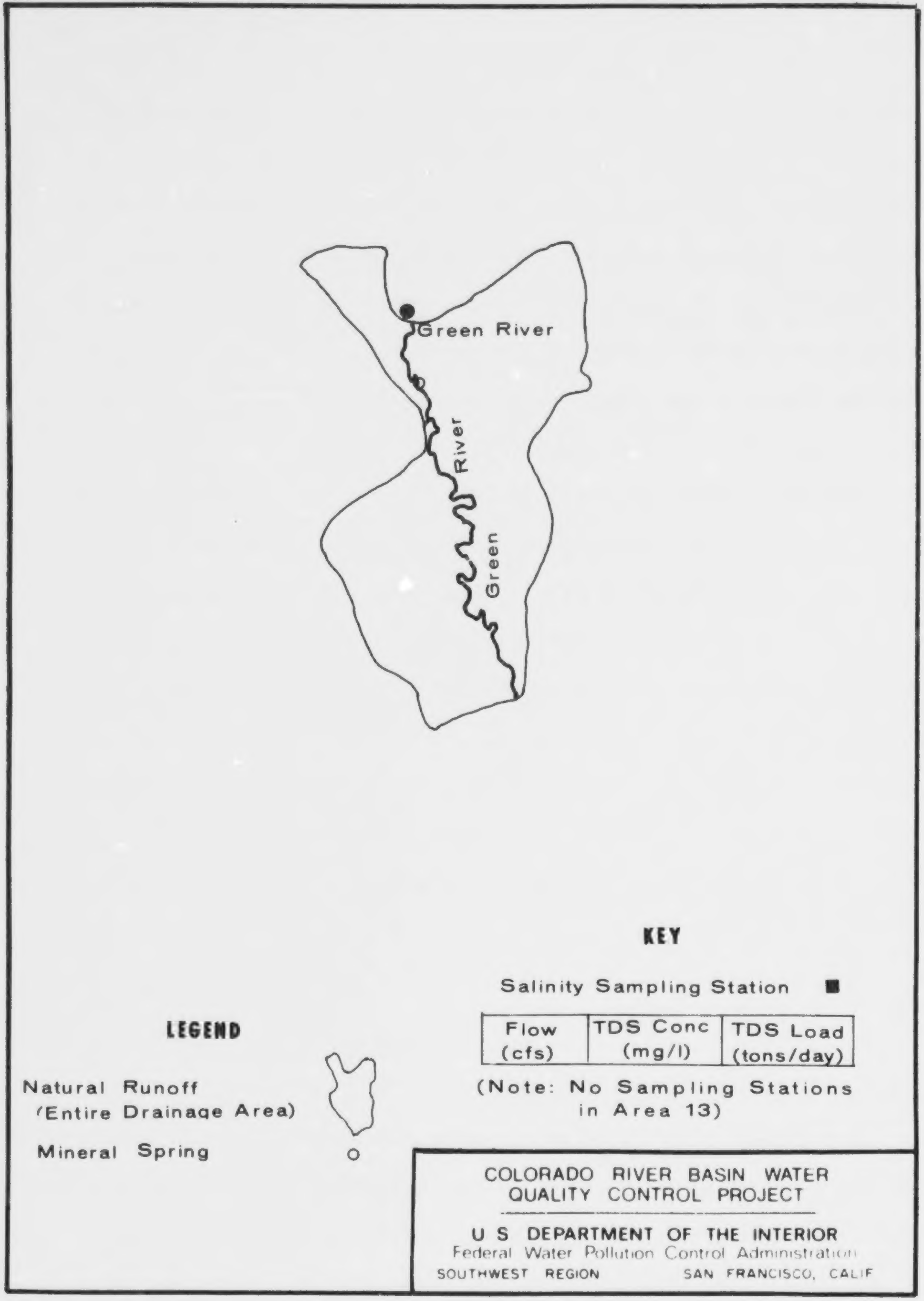

Green River
Green River
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc (mg/l)
TDS Load (tons/day)
(Note: No Sampling Stations in Area 13)
LEGEND
Natural Runoff (Entire Drainage Area)
Mineral Spring ○
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U S DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF

Figure 29 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 13. Upper Colorado River Basin, 1965–66

of Green River and the small village of Thompson are the only population centers in the area.

The study area is located in the "Canyon Lands" section of the Colorado Plateau, an area characterized by young to mature canyon plateaus with high relief. The northern portion of the area is underlain by Mancos shale. In the southern portions of the area, streams have cut deep canyons into the sandstones and shales of the San Rafael Group and the Dakota and Morrison formations, which yield moderately mineralized runoff. The Green River crosses the Little Grand fault downstream of the town of Green River. In the geologic past, the Little Grand fault served as a passageway for the upward migration of mineralized ground-water prior to the drilling of a test hole, "Crystal Geyser," which currently serves to relieve the driving pressure.

Findings. "Crystal Geyser" is the only known point source of salt in Area 13. This "geyser" erupts periodically as carbon dioxide pressure buildup in the originating formation exceeds the head required to expel accumulated water from the test hole. This source adds a salt load of 53 tons per day directly to the Green River.

The reach of the Green River immediately above its mouth is inaccessible; therefore, no outflow station for Area 13 could be established. Although it was not possible to develop a budget for this study area, mineral contributions within the area are believed to be insignificant. No perennial streams enter the Green River in Area 13, but Browns Wash and Salaratos Wash, both of which drain Mancos shale outcrops, discharge highly mineralized water during infrequent storms.

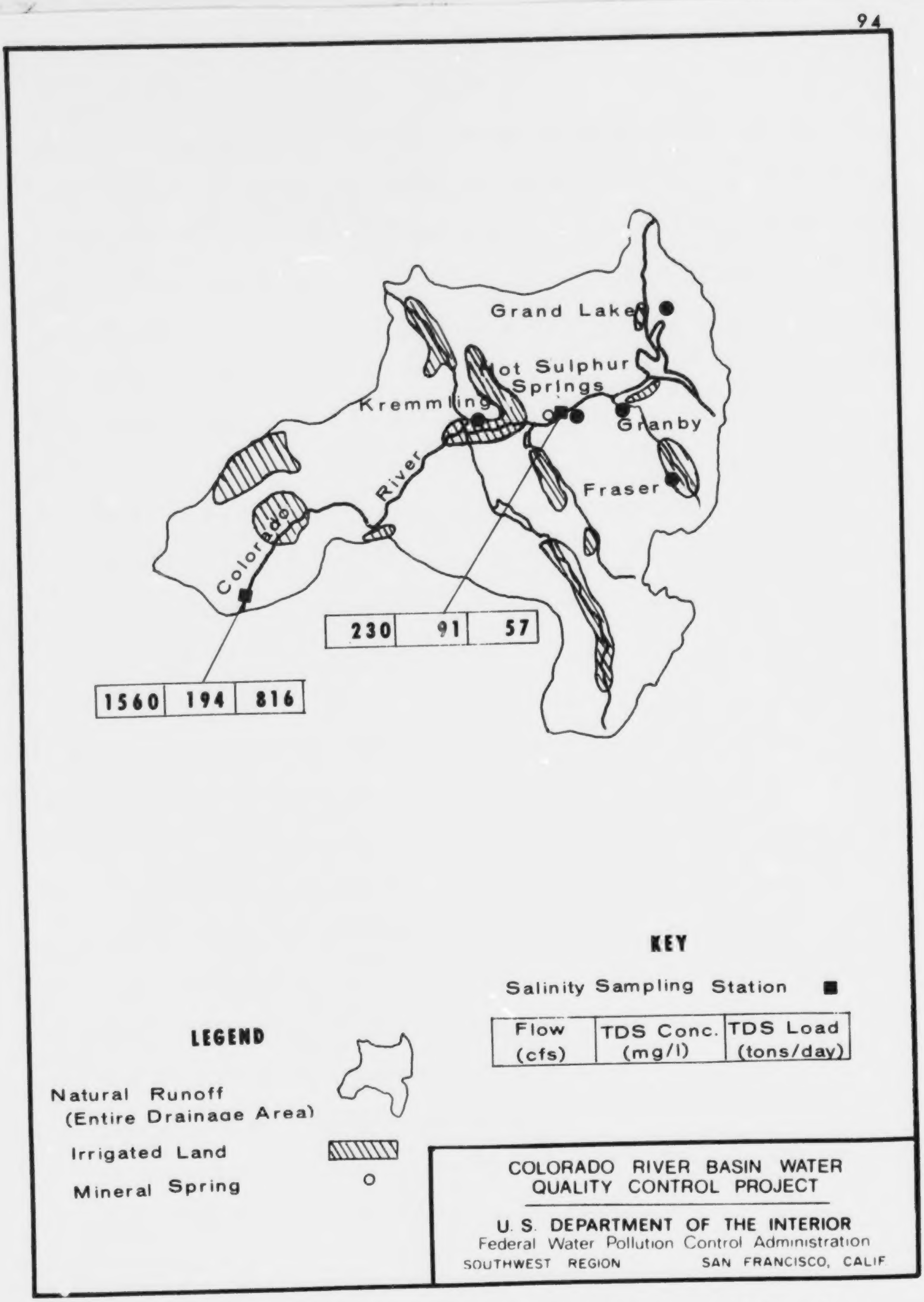

Grand Lake
Hot Sulphur Springs
Kremmling
Granby
Fraser
Colorado River
230 | 91 | 57
1560 | 194 | 816
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land
Mineral Spring
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF.

Figure 30 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 14. Upper Colorado River Basin, 1965–66

River. In the reach between Hot Sulphur Springs and Kremmling the increase in mean flow and salt load amounted to 25 cfs and 92 tons per day. Tributaries within this reach include Williams Fork, Reeder Creek, Troublesome Creek, East Troublesome Creek, Muddy Creek, and the Blue River. These tributaries add approximately 30 tons of salt per day to the Colorado River. Irrigation of approximately 24,000 acres in the Colorado River Valley, upstream of Kremmling, added 61 tons of salt per day to the stream system. This yield averages 0.9 tons per acre per year.

The Muddy Creek drainage area contributed a total salt load of 82 tons per day of which 32 tons per day were from runoff, and 46 tons were attributable to the irrigation of 7,000 acres within the Muddy Creek area. The salt yield from irrigation averaged 2.4 tons per acre per year.

Flow and salt load increases in the Colorado River between Kremmling and the mouth of the Eagle River were 588 cfs and 474 tons per day, respectively. These figures indicate the low mineral content of runoff from this area and are directly related to the insoluble character of the rock which outcrops throughout much of the tributary area.

Chemical composition of the Colorado River at Hot Sulphur Springs was typical of a headwater stream. The shape of the composition diagram is roughly triangular, with calcium and bicarbonate concentrations predominant, and sodium and chloride present only in small amounts (Figure 47). Downstream stations show an increase in the proportions of magnesium and sulfate concentrations due to the influence of irrigation return flows.

The salt budget for Area 14 is given in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Springs	<1	0.1
Irrigation	122	14.9
Runoff	694	85.0
Total	817	

Study Area 15 (Upper Main Stem)

Description. Area 15 includes the drainage areas of the Eagle and Roaring Fork Rivers and the Colorado River watershed between the mouth of the Eagle River and the USGS gage at Silt, Colorado (Figure 31). The area covers some 3,200 square miles in Eagle, Garfield, Pitkin, and Mesa Counties of Colorado. The communities of Glenwood Springs, Aspen, and several other smaller settlements are located in the area.

The higher mountain areas are underlain by resistant, insoluble rock formations which yield large volumes of high quality water. The valleys of the Eagle River below Gypsum and the Roaring Fork River between Carbondale and Glenwood Springs are cut into more easily eroded rock including the gypsum and anhydrite of the Paradox formation. These lower areas receive less precipitation and yield smaller quantities of runoff, but ground-water and runoff from these areas are highly mineralized.

Findings. The Eagle River upstream of Redcliff, Colorado, contained TDS concentrations of 120 mg/l, or less, throughout the year of study. Cross Creek above Minturn, Colorado, had TDS concentrations of less than 50 mg/l. These low concentrations of TDS demonstrate the insoluble character of the bedrock underlying the headwater areas.

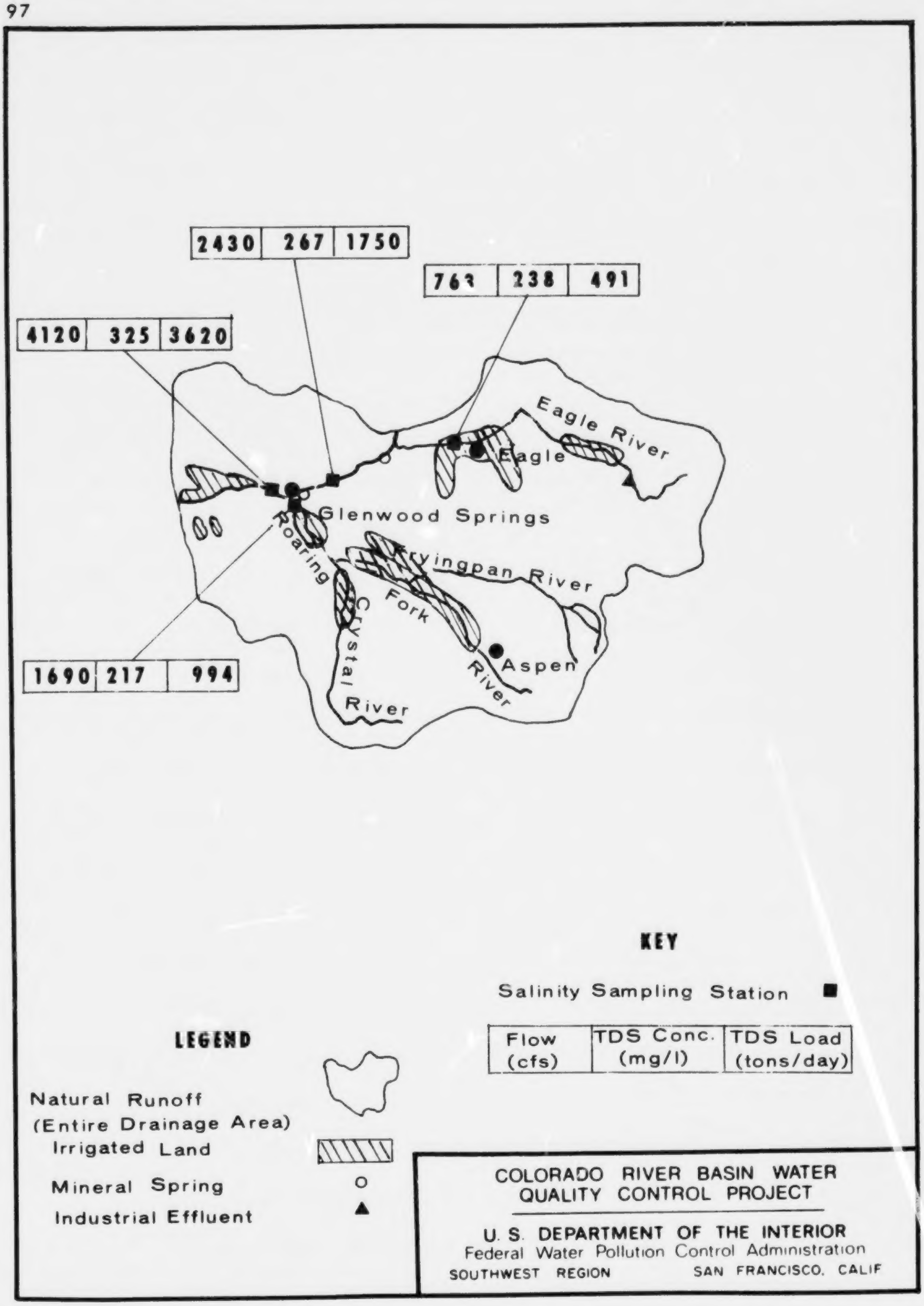

2430 | 267 | 1750
763 | 238 | 491
4120 | 325 | 3620
1690 | 217 | 994
Eagle River
Eagle
Glenwood Springs
Roaring Fork River
Fryingpan River
Crystal River
Aspen
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land ▨
Mineral Spring ○
Industrial Effluent ▲
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF

Figure 31 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 15, Upper Colorado River Basin, 1965–66

The New Jersey Zinc Corporation mine and mill at Gilman, Colorado, discharges process waste to a tailings pond located near the mouth of Cross Creek. The decanted tailings liquor is discharged into Cross Creek, and adds approximately 10 tons of salt per day to the stream system. Ground-water moving through an old tailings area, at this location, also picked up acid and dissolved metals which were then carried into the Eagle River. The toxic materials which entered Eagle River and Cross Creek eliminated aquatic life in the immediate reaches of both streams. Since the completion of the study, the New Jersey Zinc Corporation has installed pumps which collect and return the toxic seepage to the tailings area.

Salt load in the Eagle River at Edwards, Colorado, varied from 130 tons per day during the winter months to more than 600 tons per day during the spring runoff period. Much of this salt load is contributed by ground-water seeping from mineralized formations which outcrop in the area, and leaching from irrigated areas underlain by saline formations upstream of Edwards. It was not possible to separate these ground-water and irrigation effects. Brush Creek, another Eagle River tributary, contributed approximately 60 tons of salt per day, of which approximately 10 tons per day were from small irrigated areas. The remainder of the salt load was due to natural runoff from the outcrop of the highly saline Paradox formation.

The quality of Gypsum Creek was determined at its mouth at Gypsum, Colorado, but it was not possible to obtain accurate flow measurements at this point; therefore, no salt load contribution could be calculated.

Total dissolved solids concentrations at the mouth of Gypsum Creek ranged from 400 to 1,250 mg/l during the study period. These concentrations were observed below an area underlain by gypsum of the Paradox formation and downstream of 6,400 acres of irrigated land.

The salt load of the Eagle River above the mouth of Gypsum Creek was 491 tons per day during the study period. The salt load contribution by Gypsum Creek is not included in this total. A total salt load increase of 938 tons per day occurred within the reach of the Colorado River in Study Area 15. Mineral springs, located on both banks of the Colorado River approximately 2½ miles below the mouth of the Eagle River, and minor tributary inflow, appeared to be responsible for virtually all of the 447 tons of salt per day increase which is not otherwise accounted for.

Thermal springs in the vicinity of Glenwood Springs added 11.5 cfs and 585 tons of salt per day to the Colorado River. Flow from one of the major springs, not included in the above total, is used in a large outdoor swimming pool at Hot Springs Lodge in Glenwood Springs. Flow from this spring is also used to heat the lodge and to convey raw sewage from the lodge to the Colorado River. Discharge from the lodge was 7 cfs and the salt load was calculated at 333 tons per day. Mineral springs located in the area below Eagle River and above the mouth of Roaring Fork River add a salt load of approximately 1,360 tons per day to the stream system.

During the year of study, the Roaring Fork drainage area yielded a mean flow of 1,694 cfs, and a salt load of 994 tons per day. The drainage area of Roaring Fork River above Basalt yielded 64 percent of the flow, but only 39 percent of the salt load. The Fryingpan River above Basalt yielded 18 percent of the flow but only 7.5 percent of the salt load in the Roaring Fork drainage area. Crystal River at Carbondale yielded 26 percent of the flow in the Roaring Fork system, and 19 percent of the salt load. Direct runoff to the Roaring Fork River from small tributaries and ground-water inflow was calculated to yield 145 tons of salt per day. Irrigation of 21,000 acres in the Roaring Fork drainage area contributed a salt load of 200 tons per day or an average of 3.5 tons per acre per year. This irrigation occurs on lands underlain by saline material derived largely from the Paradox formation.

In the reach of the Colorado River between the mouth of Roaring Fork River and the USGS gage at Silt, increases of 136 cfs and 212 tons of salt per day were observed. Approximately 25 cfs and 16 tons per day of these increases were attributable to runoff in Canyon Creek. Elk Creek yielded approximately 50 cfs and 40 tons of salt per day. Natural runoff contributed approximately 56 tons of salt per day and irrigation of 16,000 acres contributed approximately 100 tons per day to the Colorado River. The salt yield from irrigation averaged approximately 2.3 tons per acre per year.

The chemical composition of the Eagle and Roaring Fork Rivers was very similar and reflected the influence of outcrops of gypsum and anhydrite of the Paradox formation over which the streams flow. The composition pattern diagrams for the Colorado River show increases in chloride and sodium due to the springs at Dotsero and Glenwood Springs (Figure 47). The mineral springs in this area also add radioactive elements to the river system.

The salt budget for Study Area 15 is shown in the following tabulation.

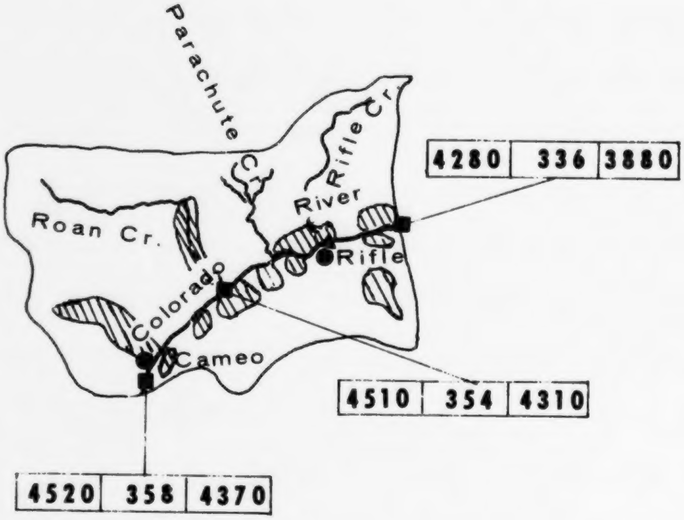
Source	TDS Load (tons/day)	Percent of Total Load
Industrial Effluents	10	0.3
Springs	1,360	44.4
Runoff	1,384	45.2
Irrigation	310	10.1
Total	3,064	

Study Area 16 (Upper Main Steam)

Description. Area 16 includes the drainage area of the Colorado River between the USGS gages at Silt and Cameo, Colorado. The area covers 1,375 square miles in Garfield and Mesa Counties of Colorado. The significant tributaries within the area are Rifle, Parachute, and Roan Creeks. Rifle which had a 1960 population of 2,135 is the principle community in the area. Elevations range from less than 5,000 feet to more than 11,000 feet. Precipitation varies from about 12 to more than 30 inches per year.

With the exception of minor mesa areas along the south boundary of the study area and the headwaters of East Rifle Creek, Area 16 is underlain by sediments containing saline minerals which result in mineralized runoff. (Figure 32)

Findings. During the year of the study, flow within Area 16 increased by 240 cfs and 490 tons of salt per day were added to the system. Approximately one ton of the load was contributed by sewage effluents from the towns of Rifle and Silt. Forty tons of salt per day were added by effluent from the Union Carbide Nuclear Corporation uranium mill at Rifle, Colorado. An additional undetermined amount of salt was added by seepage from the tailings pond at this location. The mill is located on highly pervious Colorado River alluvium and much of the process water from the mill is discharged into ponds constructed on this alluvium. Water from


Parachute Cr.
Rifle Cr.
River
Roan Cr.
Rifle
Colorado
Cameo
4280 | 336 | 3880
4510 | 354 | 4310
4520 | 358 | 4370

KEY

Salinity Sampling Station ■

Flow (cfs)	TDS Conc. (mg/l)	TDS Load (tons/day)

LEGEND

Natural Runoff (Entire Drainage Area)	▢
Irrigated Land	▨
Industrial Effluent	▲

COLORADO RIVER BASIN WATER
QUALITY CONTROL PROJECT

U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION SAN FRANCISCO, CALIF.

Figure 32 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 16, Upper Colorado River Basin, 1965–66

the ponds infiltrates to the ground-water body and moves downgrade to intersect the river. Determination of the salt load added by this seepage would require further investigation of ground-water conditions in the mill area.

During the study period, TDS concentrations in Roan Creek near DeBeque varied from 600 mg/l to 1,700 mg/l with most values ranging between 800 and 850 mg/l. TDS concentrations at the mouth of Roan Creek ranged from 1,200 to 2,400 mg/l. During most of the study period the salt load in Roan Creek near DeBeque, above the irrigated area, was greater than the salt load in Roan Creek at its mouth. This loss indicated that irrigated areas within the reach may have been storing salt. The negative salt balance resulted from an insufficient application of irrigation water to leach the salt.

Only minor changes in chemical composition of the Colorado River occurred within Area 16. There was a slight increase in sulfate concentration in proportion to other constituents.

The salt budget for Study Area 16 is given in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Irrigation	30	6.1
Industrial Effluent	40	8.2
Runoff and Industrial Wastes[1]	420	85.7
Total	490	

Study Area 17 (Upper Main Stem)

Description. Area 17 consists of the drainage area of the Colorado River between USGS gaging stations near Cameo and near Loma, Colorado, excluding the Gunnison River drainage area. The study area covers approximately 1,866 square miles in Mesa County, Colorado, and Grand County, Utah. Major tributaries which enter this reach of the Colorado River include Plateau, Ashbury, and Salt Creeks. Principle communities within the area and their 1960 population are Grand Junction, 18,694; and Fruita, 1,830. Smaller communities in the area include Loma, Appleton, Clifton, Palisade, Fruitvale, and Cameo (Figure 33).

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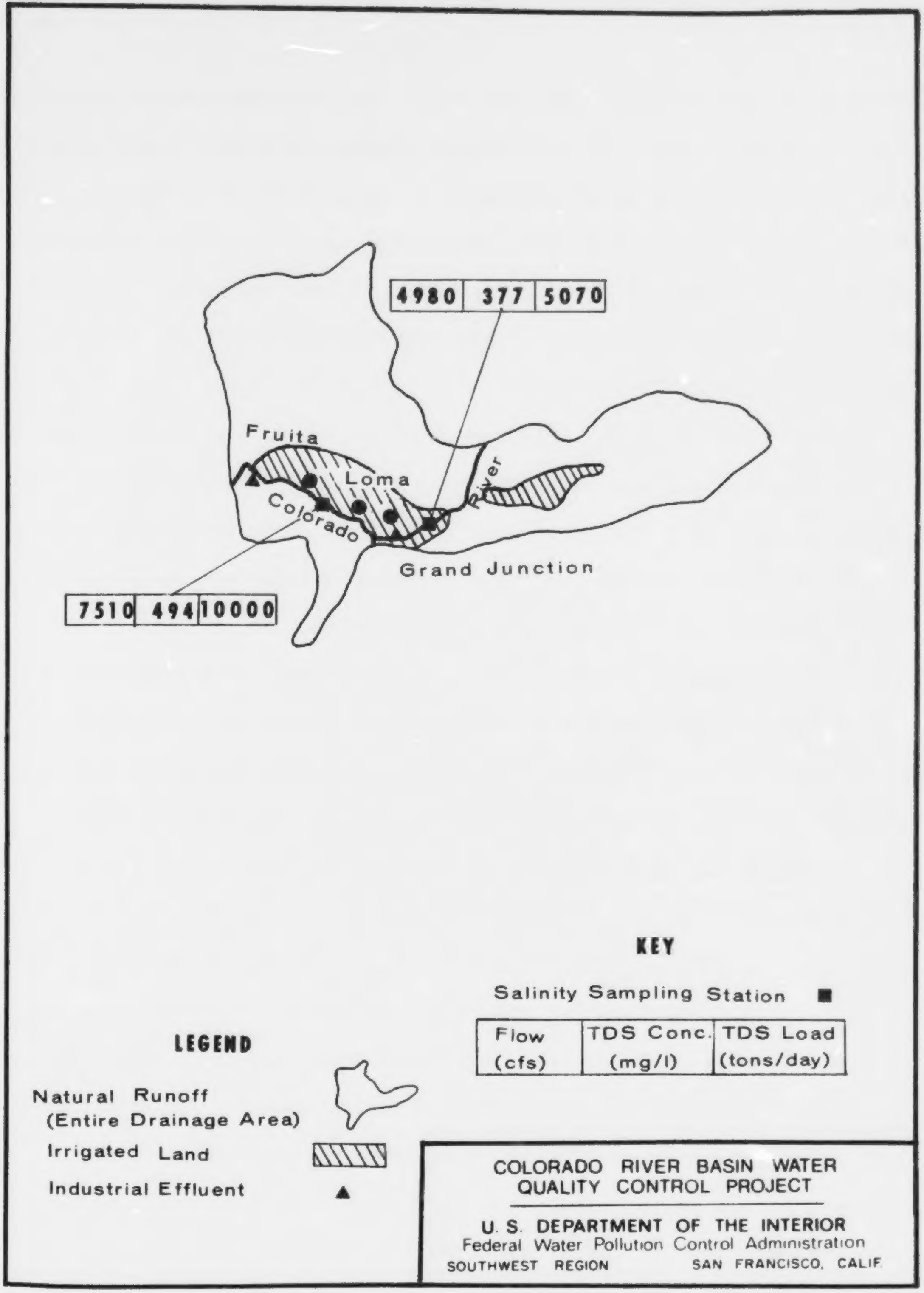
[1] Salt loads contributed by effluent ground-water and seepage from industrial waste ponds in the Rifle area could not be separated at the time of the study.

A major portion of the study area is within the valley carved by the Colorado River and is bounded on the north and west by the Roan Cliffs and Book Cliffs and on the east by the Grand Mesa. Elevations range from less than 4,500 feet at the Loma gaging station to more than 10,000 feet in the headwaters of the Plateau Creek on Grand Mesa.

Quality of runoff is directly related to the underlying rock formations. Grand Valley is underlain by gypsiferous Mancos shale. Groundwater and runoff from this area contain high concentrations of calcium sulfate. The lava capped Grand Mesa yields most of the runoff in Area 17. This runoff is of excellent quality due to the insoluble nature of the lava formations.

Findings. During the study period, direct discharge of effluent from the Climax Uranium Mill at Grand Junction contributed a salt load of 35 tons per day to the system. The "South Sewage Treatment Plant" at Grand Junction contributed approximately 5 tons of salt per day, and the "West Sewage Treatment Plant" added approximately 11 tons per day. Effluent from the American Gilsonite Corporation Plant near Fruita added approximately 9 tons of mineral salts per day to the river. Direct


4980
377
5070
Fruita
Loma
Colorado
River
Grand Junction
7510
494
10000
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land
Industrial Effluent ▲
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
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Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF.

Figure 33 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 17, Upper Colorado River Basin, 1965–66

tributary drainage in the immediate valley area added 2 tons of salt per day to the river. Irrigation of approximately 88,000 acres in the Grand Valley area added 1,925 tons of salt per day to the Colorado River, or an average yield of 8.0 tons per day per acre per year. This high salt yield, which is among the largest observed in the Colorado River Basin, is due to the highly soluble nature of the Mancos shale underlying the irrigated area.

Plateau Creek added 161 tons of salt per day to the Colorado River. It was not possible to develop an accurate salt budget for the Plateau Creek drainage, but the salt load contribution by irrigation was estimated at 60 to 82 tons per day. Thus, the total salt contribution for irrigation in Area 17 was approximately 2,000 tons per day. This amounts to 93 percent of the total salt load contribution from Area 17 and 7.7 percent of the total Upper Colorado River Basin salt load.

Chemical composition of the Colorado River within Area 17 changed significantly. Calcium increased slightly, but the relative proportions of cations remained essentially constant. The large increase in sulfate and decrease in chloride concentrations resulted from ion-exchange in the gypsum-rich Mancos soils irrigated with Colorado River water and from similar conditions in the Gunnison River drainage area.

The salt budget for Study Area 17 is tabulated below.

Scurce	TDS Load (tons/day)	Percent of Total Load
Industrial Effluents	44	2.2
Municipal Effluents	16	0.7
Runoff	90	4.1
Irrigation	2000	93.0
Total	2150	

Study Areas 18, 19, 20, and 21 (Upper Main Stem)

Description. Study Areas 18, 19, 20, and 21, comprising the Gunnison River Drainage, were combined for study as a unit because of the complex water diversions between the areas (Figure 34). The study area covers 8,000 square miles in Mesa, Delta, Gunnison, Saguache, Hinsdale, San Juan, Ouray, and Montrose Counties of Colorado. Delta, Montrose, Gunnison, Ouray, and Paonia are the principle communities in the area.

Major tributaries in the area include Tomichi Creek, Lake Fork, North Fork, and the Uncompahgre River. The headwaters of the Gunnison River, Tomichi Creek, and Lake Fork are underlain by resistant rocks which yield large quantities of high quality runoff; while the areas drained by the North Fork, the Uncompahgre, and the Lower Gunnison River are underlain by more soluble formations which result in more mineralized runoff.

Findings. The Gunnison River discharged a mean flow of 1,040 cfs and a mean salt load of 314 tons per day at Gunnison, Colorado. The salt load from irrigation upstream of Gunnison was 9 tons per day, or 0.3 tons per acre per year. Runoff from the Taylor River, East River, Ohio Creek, and directly to the Gunnison River contributed a mean flow and salt load of 1,085 cfs and 294 tons per day. The excellent quality of this runoff is directly attributable to the resistant nature of the headwaters rock formations.

Salt load budgets for the Razor Creek drainage and the irrigated areas along Tomichi Creek indicated a similar low salt yield from irrigation. The soils which were under irrigation have been well leached by the relatively high precipitation in this area.

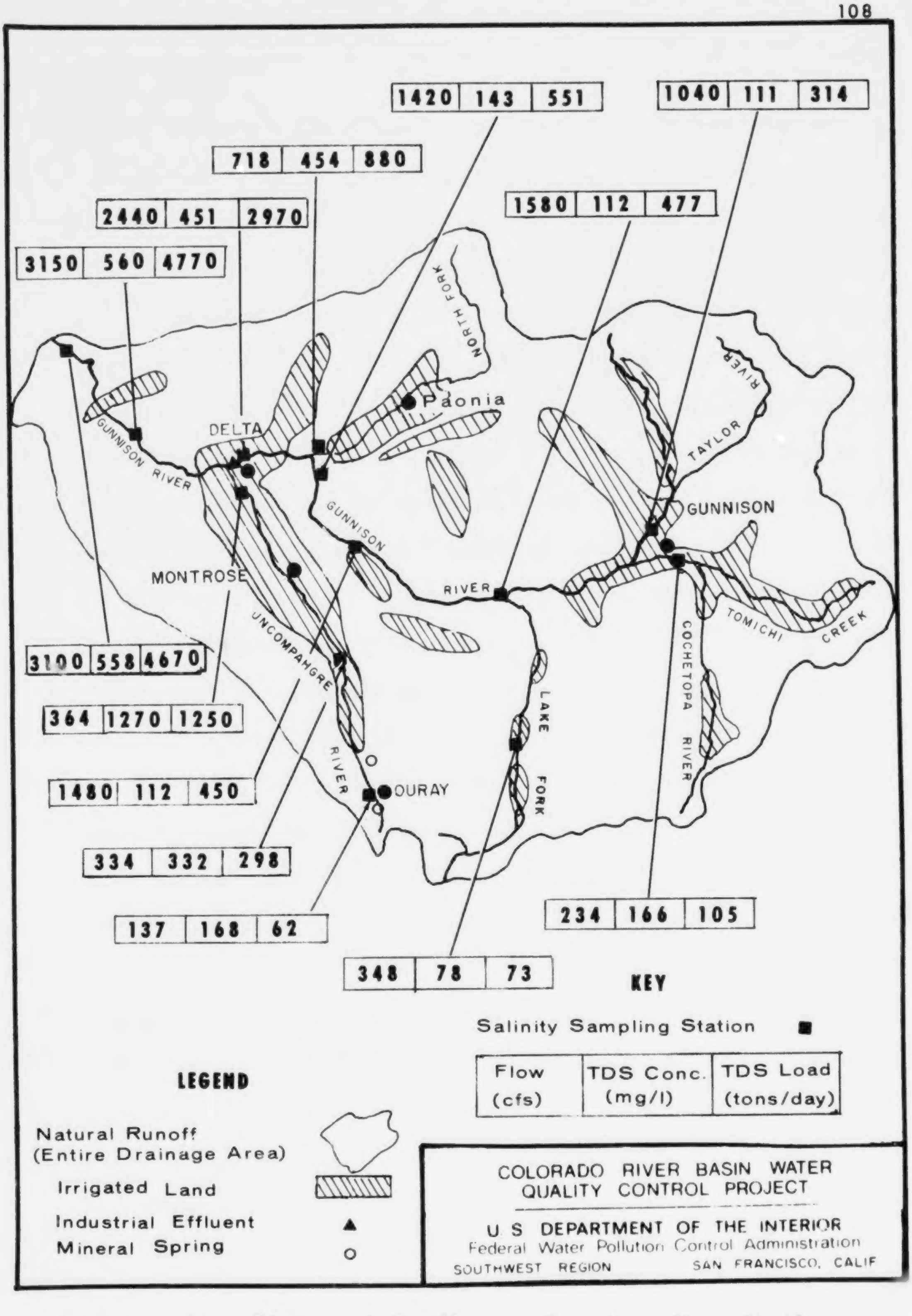
1420 | 143 | 551
1040 | 111 | 314
718 | 454 | 880
1580 | 112 | 477
2440 | 451 | 2970
3150 | 560 | 4770
NORTH FORK
Paonia
DELTA
GUNNISON RIVER
TAYLOR RIVER
GUNNISON
GUNNISON RIVER
MONTROSE
TOMICHI CREEK
UNCOMPAHGRE RIVER
COCHETOPA RIVER
LAKE FORK
OURAY
3100 | 558 | 4670
364 | 1270 | 1250
1480 | 112 | 450
334 | 332 | 298
137 | 168 | 62
234 | 166 | 105
348 | 78 | 73
KEY
Salinity Sampling Station ■
Flow (cfs) | TDS Conc. (mg/l) | TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land ▨
Industrial Effluent ▲
Mineral Spring ○
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U.S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF

Figure 34 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Areas 18,19,20,&21 Upper Colorado River Basin, 1965–66

The Lake Fork drainage area contributed a mean flow of 348 cfs and a salt load of 73 tons per day during the period of the study. About one ton per day of this total salt load was contributed by drainage from abandoned mines located in the headwaters area of Lake Fork. Irrigation of 3,800 acres in the Lake Fork watershed contributed approximately one ton per day to the total salt burden. The remainder of the salt load resulted from natural runoff, and the low yield is indicative of the highly resistant character of the igneous and metamorphic rocks underlying the area. Closure of Blue Mesa Dam on the Gunnison River during the period of study precluded development of a salt budget for that reach of the stream. During summer runoff, the area yielded approximately 1,000 cfs and 300 tons of salt per day. This yield declined to 150 cfs and 30 tons per day just prior to closure of the dam in October 1965.

The Uncompahgre River drainage area, upstream of Ouray, Colorado, yielded a mean annual flow of 137 cfs and a salt load of 62 tons per day. Drainage from active and abandoned mines in the area above Ouray yielded approximately 9 cfs and 13 tons of salt per day. Much of the mine drainage is highly toxic and precludes aquatic life in many of the headwater streams.

Flow from Ouray Hot Spring is collected in Box Canyon and piped downstream to a swimming pool located below Ouray. Overflow from the pool is discharged into the Uncompahgre River and adds a salt load of approximately 4.5 tons per day to the stream. Other hot mineral springs located along the Uncompahgre River, about one mile above Ridgeway, add approximately 1 cfs and 7 tons of salt per day to the stream. Water budgets for the Uncompahgre River below Ouray and above the mouth of Dallas Creek showed flows varying from a loss of 29 cfs to a gain of 278 cfs. The large variation in flow is due to the seasonal nature of the runoff and the diversion of water for irrigation. The mean annual flow in the reach was 28 cfs and the mean salt load was 124 tons per day. Irrigation of 6,000 acres in the Uncompahgre River Valley consumed 7 cfs and added 74 tons of salt per day to the stream. The salt yield from irrigation which was calculated to average 4.5 tons per acre per year, was attributable to leaching of minerals from saline soils of the area. Runoff from soluble sedimentary outcrops within the Region contributed approximately 50 tons of salt per day. Losses in salt load, within the reach of the Uncompahgre River between Ridgeway and Colona, indicated the possibility of salt storage in irrigated lands.

Water and salt budgets for the Lower Gunnison Valley in the vicinity of Montrose and Delta are highly complex. A detailed discussion of sources and changes in mineral quality within this reach is available in an open file report at the Project Office in Denver, Colorado. Irrigation of 164,000 acres in Gunnison Valley, most of which is underlain by gypsiferous Mancos shale, yielded a salt load of approximately 3,000 tons per day or an average 6.7 tons per acre per year. This high yield results from application of irrigation water to soils derived from the Mancos shale.

During the year of study, the Gunnison River Basin yielded a mean annual flow of 3,100 cfs and a mean salt load of 4,670 tons per day. The 3,000 tons per day from irrigation in the Lower Gunnison River Basin represents 64 percent of the total salt load additions to the area.

An additional salt load of 100 tons per day was contributed by irrigation throughout the remainder of the Gunnison Basin.

The chemical composition of the upper reaches of the Gunnison River, Tomichi Creek, and Lake Fork was typical of headwater streams derived from highly resistant rock formations. In the lower reach of the Gunnison River, there was a significant change in chemical composition which was caused by runoff from the North Fork of the Gunnison River and irrigation in the vicinity of Delta. Solution of saline minerals in the Mancos shale in this area caused calcium and sulfate to predominate.

Chemical composition of the upper reaches of the Uncompahgre River was unusual for headwater streams in that calcium and sulfate predominated. The high concentration of these chemicals was due primarily to mine drainage and natural oxidation of sulfide minerals in the Red Mountain Creek drainage area. Calcium and sulfate were predominate throughout the lower reaches of the Uncompahgre and Gunnison Rivers due to irrigation return flows and runoff from the widespread gypsiferous Mancos shale in the area.

The salt budget for Study Areas 18, 19, 20, and 21 is shown in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Municipal	36[1/]	0.8
Irrigation	3100	66.4
Mine drainage	14	0.3
Runoff and Springs	1520	32.5
Total	4670	

[1/] Includes ungaged infiltration to the Delta sewage collection system.

Study Area 22 (Upper Main Stem)

Description. Study Area 22 consists of the Colorado River watershed between Loma, Colorado, and the mouth of the Dolores River (Figure 35). It covers an area of approximately 1,190 square miles in northeastern Grand County, Utah, and northwestern Mesa County, Colorado. Tributaries within the area include the Little Dolores River, Westwater Creek, Bitter Creek, and Cottonwood Wash, all of which yield insignificant runoff.

The area is characteristic of the Colorado Plateau with steep-walled buttes rising high above the valleys occupied by intermittent streams. The tops of the buttes are forested while the valleys are generally barren. Elevations in the area range from 4,000 to 9,500 feet. Annual precipitation ranges from slightly less than 8 inches, along the river, to more than 20 inches at high elevations. The total area yields insignificant runoff.

Findings. There were no significant salt load additions by tributaries during the study period, and there were no consumptive losses within the reach other than evapotranspiration by phreatophytes in the valleys. During the study period, flow within this area decreased by 70 cfs and the salt load decreased by 60 tons per day. The observed changes in flow and salt loading are well within the limits of accuracy of stream measurement and sampling analysis. Small decreases in flow; however, may have occurred due to evapotranspiration. Some precipitation of minerals may also have occurred within the Colorado River reach in Study Area 22.

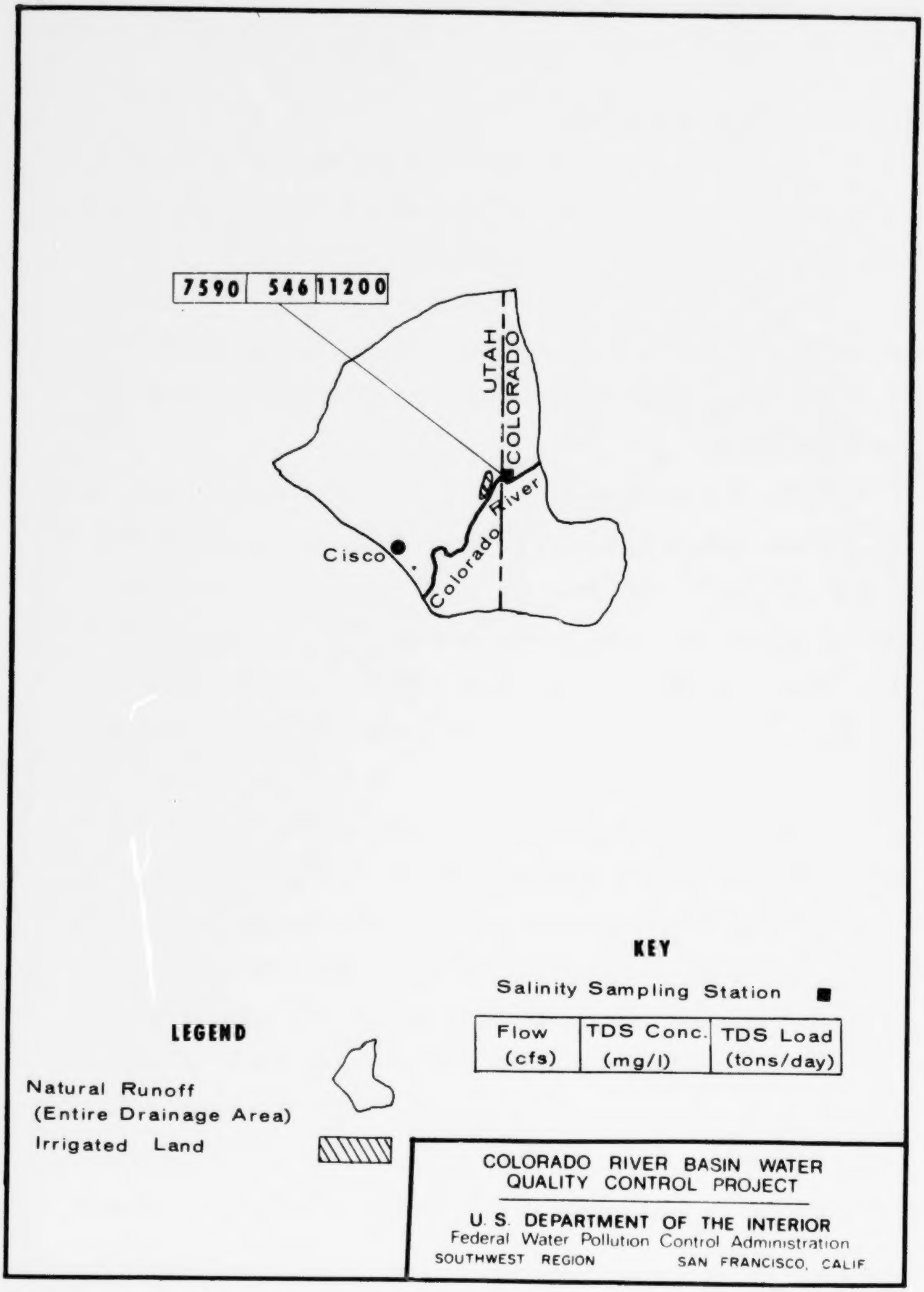
7590
546
11200
UTAH
COLORADO
Colorado River
Cisco
KEY
Salinity Sampling Station
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
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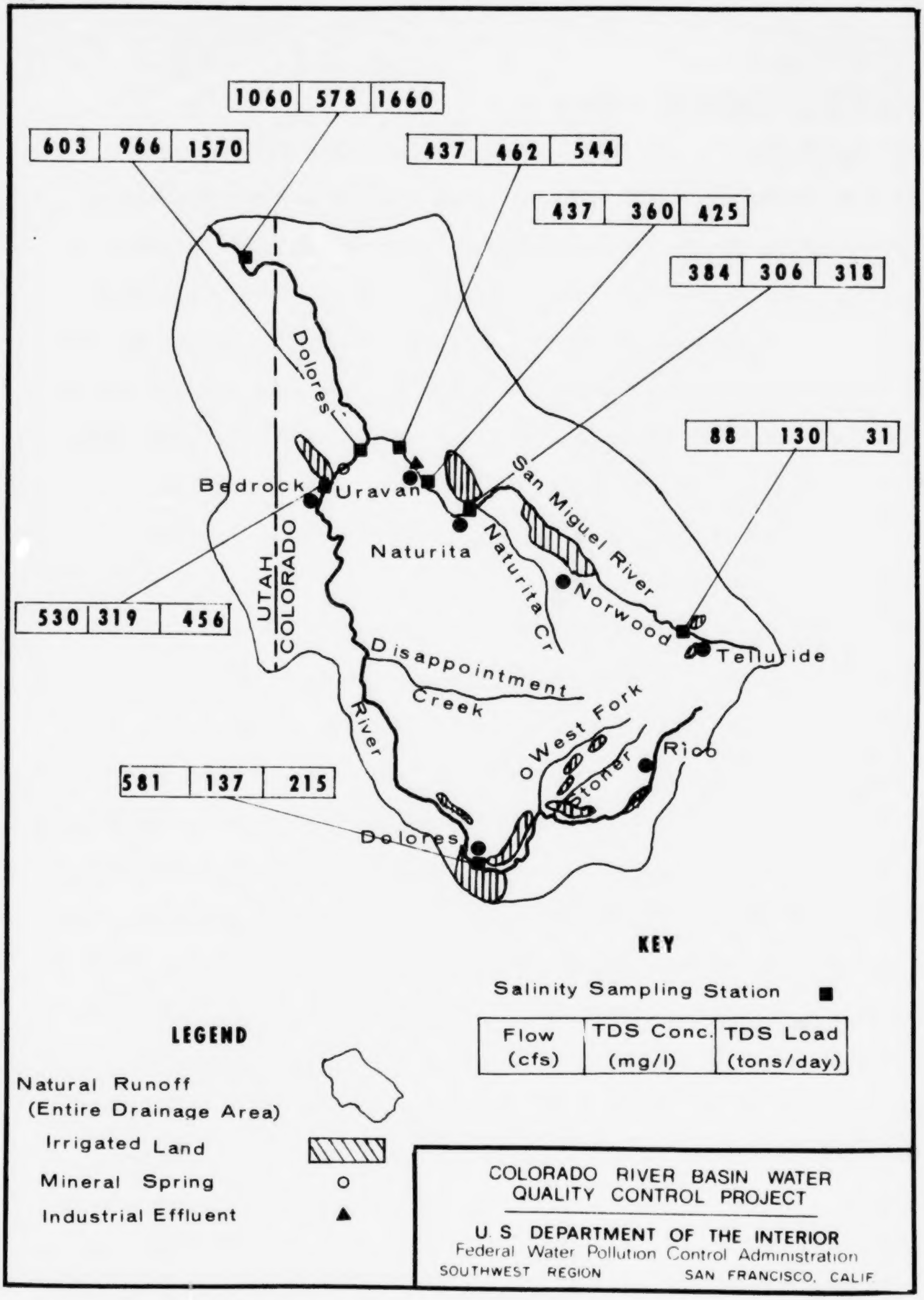
Figure 35 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 22, Upper Colorado River Basin, 1965–66

Study Area 23 (Upper Main Stem)

Description. Study Area 23 includes the entire drainage area of the Dolores and San Miguel Rivers (Figure 36). It covers 4,536 square miles in Montezuma, Dolores, San Miguel, Montrose, and Mesa Counties, Colorado, and in Grand and San Juan Counties, Utah. There are no communities of significance from the standpoint of effects on water quality. Active and inactive mines and mills within the area have profound effects on water quality. Elevations of the area range from 4,200 feet to more than 14,000 feet. The Dolores River and its major tributary, the San Miguel River, head in the alpine topography of the San Juan Mountains, in a region of high precipitation and resistant rocks. Most of the streamflow comes from these areas which comprise less than 10 percent of the study area. Downstream areas yield less runoff, having higher concentrations of TDS.

Findings. The highly resistant rocks upstream of Dolores yield large volumes of high-quality water. During the study period, the Dolores River at Dolores yielded a mean annual discharge of 580 cfs, and a mean salt load of 215 tons per day. Approximately 6 tons per day of this load were attributable to drainage from three mines in the Rico area. This drainage also contains high concentrations of heavy metals which limits aquatic life in the Dolores River. Stoner Creek discharged water with TDS concentrations of from 70 to 150 mg/l and the West Fork of the Dolores River had concentrations ranging from 100 to 350 mg/l. Paradise Hot Springs, located on the West Fork of the Dolores River, discharged water with a TDS concentration of 5,500 mg/l. This salt spring contributed a salt load of 1.7 tons per day and partially accounts for the higher


1060 | 578 | 1660
603 | 966 | 1570
437 | 462 | 544
437 | 360 | 425
384 | 306 | 318
88 | 130 | 31
530 | 319 | 456
581 | 137 | 215
Dolores
Bedrock
Uravan
Naturita
Naturita Cr
San Miguel River
Norwood
Telluride
UTAH
COLORADO
Disappointment Creek
River
West Fork
Stoner
Rico
Dolores
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land ▨
Mineral Spring ○
Industrial Effluent ▲
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
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Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF

Figure 36 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 23, Upper Colorado River Basin, 1965–66

mineral concentrations in West Fork. A small amount of irrigation may also contribute some salt to the West Fork. Much of the flow in the Dolores River is diverted into the McElmo Creek Basin. This diversion of high-quality water deprives the Dolores River system of dilution water in the downstream reaches.

Disappointment Creek, which flows over Mancos shale throughout its entire length, discharged salt loads of from 3 to 142 tons per day to the Dolores River. The runoff of Disappointment Creek was highly mineralized throughout the year.

The Dolores River at Bedrock discharges a mean annual flow of 530 cfs and a mean salt load of 456 tons per day. This reflects a decrease of 50 cfs and an increase of 240 tons per day over the stream reach between Dolores and Bedrock. The decrease in flow resulted from the diversion of water to the McElmo Creek Basin. This diversion also carried a small amount of salt out of the Dolores River Basin.

In the reach of the Dolores River between Bedrock and the mouth of the San Miguel River, water quality is severely degraded by solution of minerals in Paradox Valley. The mean salt load addition, due to solution of minerals from the Paradox Valley salt anticline, was calculated to be 688 tons per day. A detailed discussion of the geohydrologic conditions which are responsible for this major salt load is available in an open file report at the Project Office in Denver, Colorado.

The San Miguel River below Telluride had a mean flow of 88 cfs and a mean salt load of 31 tons per day, reflecting the high quality of runoff from the San Juan Mountains. This salt load included approximately 4 tons per day from several active and abandoned mines in the headwaters area. The Idarado Mining Corporation mill above Telluride adds small amounts of salt through seepage from a tailings pond.

In the reach of the San Miguel River between Telluride and Naturita, flow increased by 296 cfs and the salt load increased by 287 tons per day. The South Fork of the San Miguel River contributed 30 to 150 tons of salt per day of which approximately 10 tons per day resulted from drainage from mines in the headwaters area. Naturita Creek added a salt load of approximately 70 tons per day of which 46 tons per day were attributable to irrigation of approximately 6,000 acres in the Norwood area. The salt yield attributable to irrigation averaged approximately 2.8 tons per acre per year. The remainder of the salt load increase was due to natural runoff from formations containing soluble minerals.

The San Miguel River above Uravan had a mean annual flow of 437 cfs and a mean salt load of 425 tons per day. This represents an increase of 53 cfs and 107 tons of salt per day in the reach between Naturita and Uravan which was due to diffuse groundwater inflow and overland runoff.

At the station below Uravan, there was a mean annual salt load of 544 tons of salt per day, a gain of 119 tons per day in the Uravan reach. Effluent from the Union Carbide Uranium Mill at Uravan contributed approximately 24 tons of salt per day. An unknown amount of the increase within the Uravan reach was contributed by seepage from the industrial waste holding ponds adjacent to the San Miguel River bed at the Union Carbide mill.

The mean flow and salt load in the Dolores River near Cisco was 1,060 cfs and 1,660 tons per day, respectively. This represents an increase of 20 cfs and a decrease of 454 tons per day within the reach between the mouth of the San Miguel River and the station at Cisco. The magnitude of the decrease in salt load approximated the magnitude of an unexplained increase in the Dolores River between Bedrock and the mouth of the San Miguel River. This disparity cannot be further refined in the absence of improved flow measurements on the Dolores River above the mouth of the San Miguel. The Dolores at this point is a steep, boulder-strewn canyon in which accurate flow measurement is virtually impossible.

Sinbad Valley, a small collapsed anticline similar in nature to Paradox Valley salt anticline, is drained by Salt Creek. The TDS concentrations in Salt Creek during the year of study ranged from 34,000 mg/l to 49,300 mg/l, although the salt load contributed to the Dolores was only approximately 9 tons per day. Additional salt loads may enter the Dolores River from the Salt Wash area as underflow from the alluvium in Salt Wash Canyon.

Chemical composition of the headwaters of the Dolores River was typical of headwater streams with calcium bicarbonate water of low TDS concentrations. At Bedrock, the chemical composition of the Dolores River was altered significantly by solution of minerals in Gypsum Valley and the inflow of Disappointment Creek. Ionic composition of the Dolores River, above the mouth of the San Miguel River, was altered drastically by the addition of sodium chloride and calcium sulfate from the Paradox formation.

The chemical composition of the headwaters of the San Miguel River was very similar to that of the Uncompahgre River. Both streams head in the San Juan Mountains and have calcium-sulfate type waters, reflecting the oxidation of sulfides from natural sources and from active and abandoned mines. Downstream stations on the San Miguel show essentially no change in the proportion of the mineral constituents, but do reflect substantial increases in all constituents. The Dolores River near Cisco showed an increase in the proportion of sulfate, and a decrease in the proportions of sodium and chloride, as a result of minerals contributed by the San Miguel River.

The salt budget for Study Area 23 is shown in the Following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Irrigation	46	4.8
Industrial Effluent and Seepage from Ponds	119	12.4
Springs and Salt Seeps	695	72.5
Mine Drainage	20	2.2
Runoff	780	8.1
Total	1660	

Study Area 24 (Upper Main Stem)

Description. Study Area 24 encompasses the Colorado River watershed below the mouth of the Dolores River and above the mouth of the Green River (Figure 37). It covers an area of 2,504 square miles in Grand and San Juan Counties, Utah. The area includes the community of Moab, Utah, which had a population of 4,682 in 1960. Onion Creek, Castle Creek, Salt Wash, Mill Creek, Hatch Wash, and Indian Creek contributed insignificant flow during the study period. The effluent from the Atlas Mineral Coporation uranium mill at Moab was the only significant inflow in the area. This mill added a mean salt load of 36 tons per day to the Colorado River.

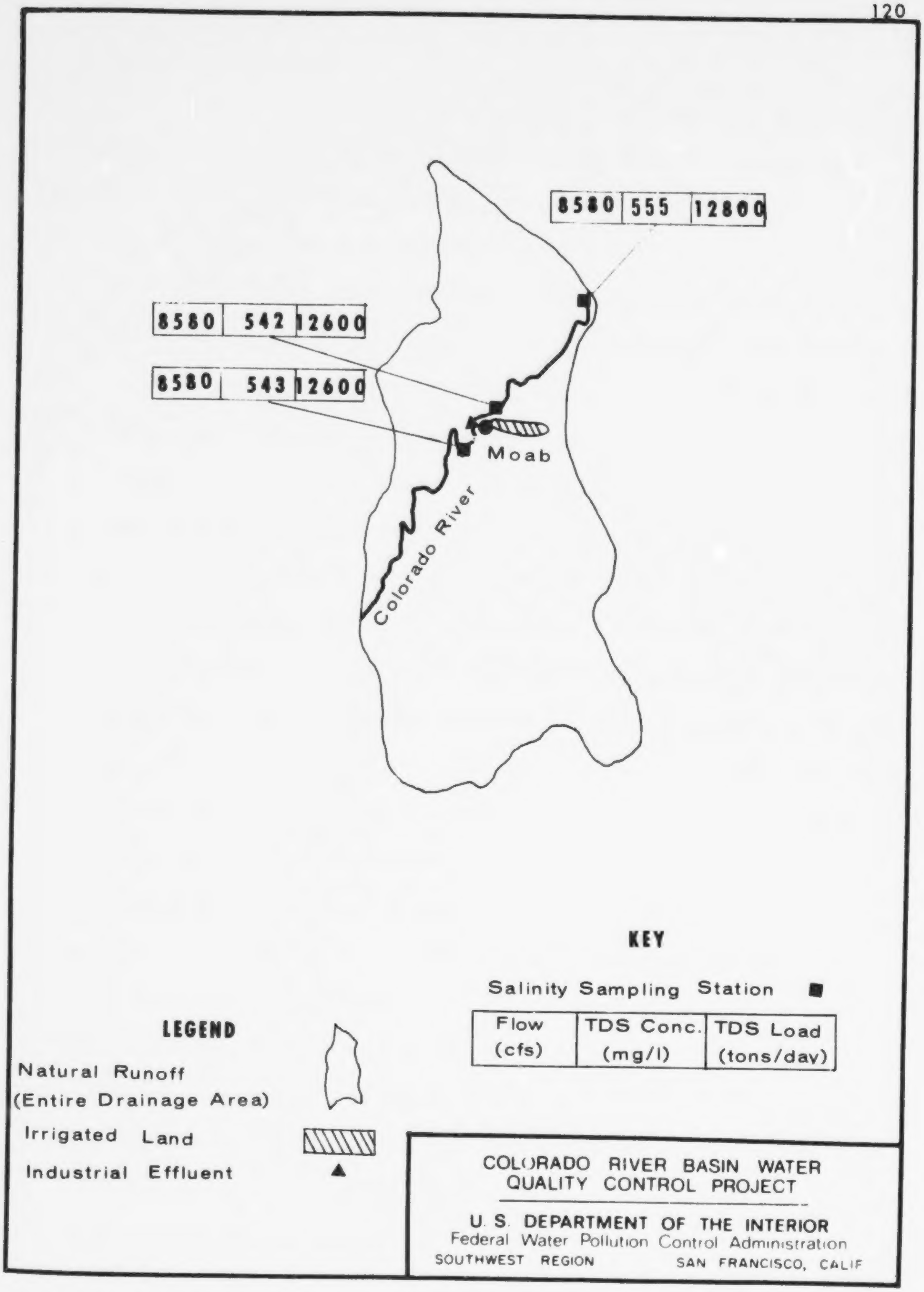
8580 | 555 | 12800
8580 | 542 | 12600
8580 | 543 | 12600
Moab
Colorado River
KEY
Salinity Sampling Station ■
Flow (cfs) | TDS Conc. (mg/l) | TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land ▨
Industrial Effluent ▲
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Figure 37 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 24, Upper Colorado River Basin, 1965–66

Study Area 25 (San Juan Subbasin)

Description. Area 25 includes the entire Dirty Devil River drainage area, which covers approximately 4,300 square miles in Wayne, Garfield, Sevier, and Emery Counties of Utah. Settlements in the area and their 1960 populations include Loa (359), Bicknell (366), Torrey (128), and Hanksville (80). The Dirty Devil River is formed at Hanksville by the junction of the Fremont River and Muddy Creek (Figure 38).

The topography consists of high block plateaus, which are partly lava capped, and young to mature canyoned plateaus with high relief. With the exception of volcanic rocks in the headwaters of the Fremont River, virtually the entire sedimentary section crossed by the Dirty Devil River and its upstream tributaries is easily eroded and yields poor quality ground-water. These conditions result in poor quality runoff downstream of Bicknell. There are only a few perennial streams within the area.

Findings. The Fremont River above the community of Fremont discharged approximately 26 cfs and a salt load of 10 tons per day during the study period. This high-quality water is derived from headwaters underlain by relatively insoluble lava flows. An increase in flow of 28 cfs and a salt load pickup of 47 tons per day was observed between the Fremont station and the station upstream of Torrey. Approximately 14 cfs and 8 tons of salt per day of this change was attributable to inflow from a spring at Loa Fish Hatchery. A salt load of approximately 20 tons per day was contributed by irrigation of 18,000 acres upstream of Torrey. The salt yield from irrigation averaged approximately 0.4 tons per acre per year.

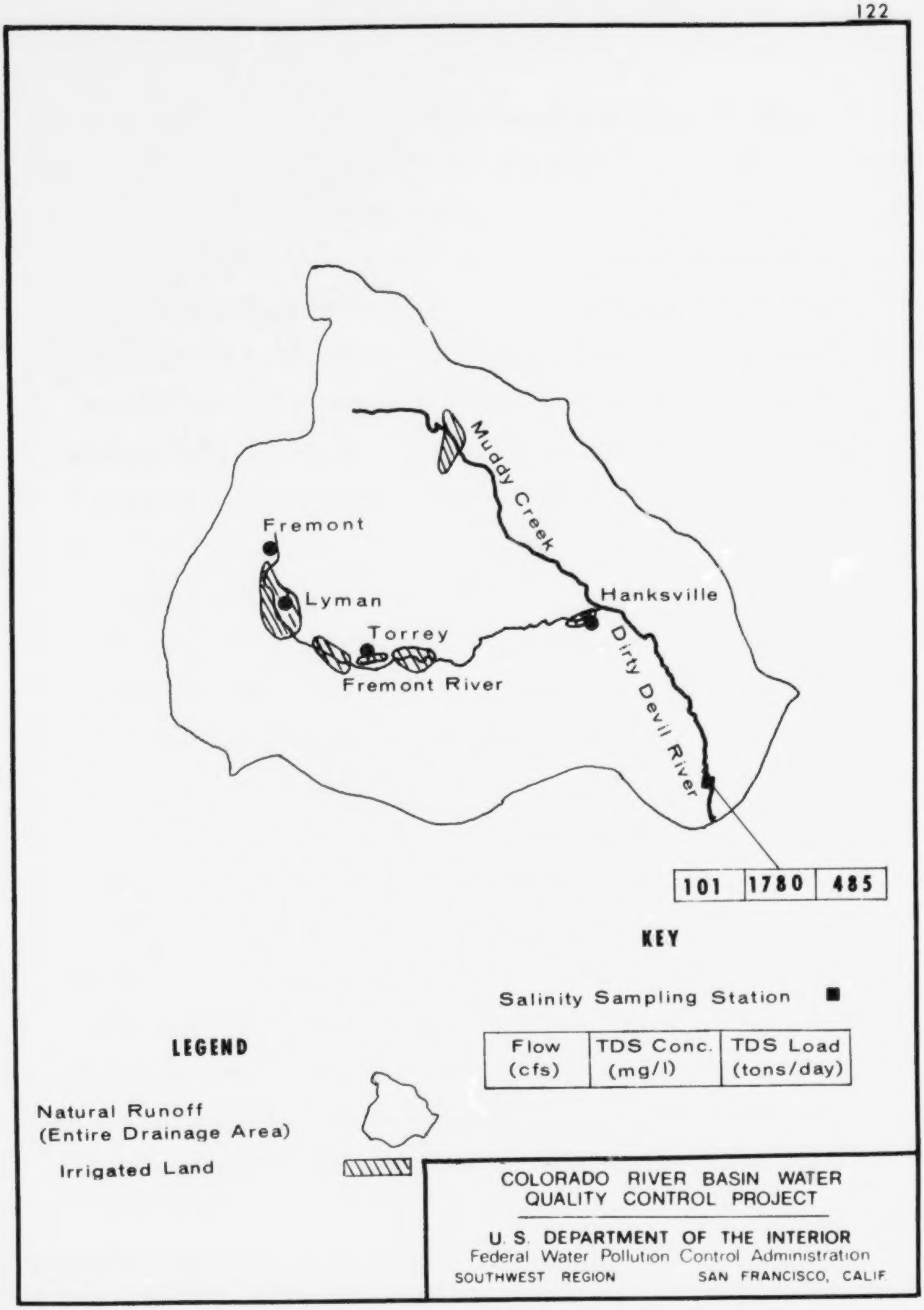
Muddy Creek
Fremont
Lyman
Torrey
Hanksville
Fremont River
Dirty Devil River
101
1780
485
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
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Figure 38 Flow and Quality at Key Sampling Stations and Location of Principal Salinity Sources in Study Area 25, Upper Colorado River Basin, 1965–66

The reach of the Fremont River between Torrey and Caineville received inflow of 9 cfs and a salt load of 33 tons per day during the study period. Virtually all of this inflow was due to natural runoff over formations which become increasingly saline in the lower reaches of the drainage area. In the reach between Caineville and the mouth of Hanksville, the Fremont River experienced a mean annual depletion of 6 cfs, but a salt load gain of 32 tons per day. The small amount of irrigation within the drainage area caused a salt load increase of about 16 tons per day. The leaching of soluble salts by runoff in the immediate drainage area also added about 16 tons per day to the system.

The waters of Muddy Creek at its mouth were highly saline during the entire study period. Concentrations of TDS ranged from 3,600 mg/l to 5,400 mg/l. Most of this salt was due to natural leaching from the Mancos shale in the Castle Valley area upstream of the San Rafael swell. Approximately 60 tons per day of the total salt load is attributable to irrigation of 7,000 acres upstream of the San Rafael swell.

The Dirty Devil River, from its origin at the junction of the Muddy and Fremont Rivers to its mouth at Lake Powell, flows through remote, uninhabited areas. The area contributed almost no runoff, but some salts are added to the system by leaching from the streambed and banks. The Dirty Devil River contributed 101 cfs and a salt load of 485 tons per day.

Waters of the Dirty Devil River were of calcium-sulfate type, which reflected leaching of gypsum from the Mancos shale outcrop area along the Fremont River.

The salt budget for Study Area 25 is given in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Irrigation	96	19.8
Springs	8	1.6
Runoff	381	78.6
Total	485	

Study Area 26 (San Juan Subbasin)

Description. Area 26 consists of the Colorado River drainage area between the mouth of the Green River and Lees Ferry, Arizona, excluding the drainage area of the Dirty Devil and San Juan Rivers (Figure 39). This extremely remote area receives little inflow, and yields almost no runoff, except from the highlands along the western boundary of the area. Two streams, the Escalante and Paria Rivers, discharge to the Colorado River within this reach. The Escalante River heads on the Great Basin Divide west of the town of Escalante, Utah, where formations are relatively resistent to weathering. The formations which make up the drainage area of the Paria River are easily eroded, as is evidenced by the bizarre structure in Bryce Canyon.

Findings. Runoff from the area during the study period was practically nil. Total dissolved solids concentrations in the Escalante River were usually on the order of 300 to 400 mg/1. Concentrations of TDS in the Paria River usually exceeded 1,000 mg/1. The salt load from the entire drainage area had virtually no effect on the Colorado River during the period of study.

Study Areas 27 and 28 (San Juan Subbasin)

Description of Area 27. This study area includes the San Juan River watershed upstream of Shiprock, New Mexico, excluding the Animas and

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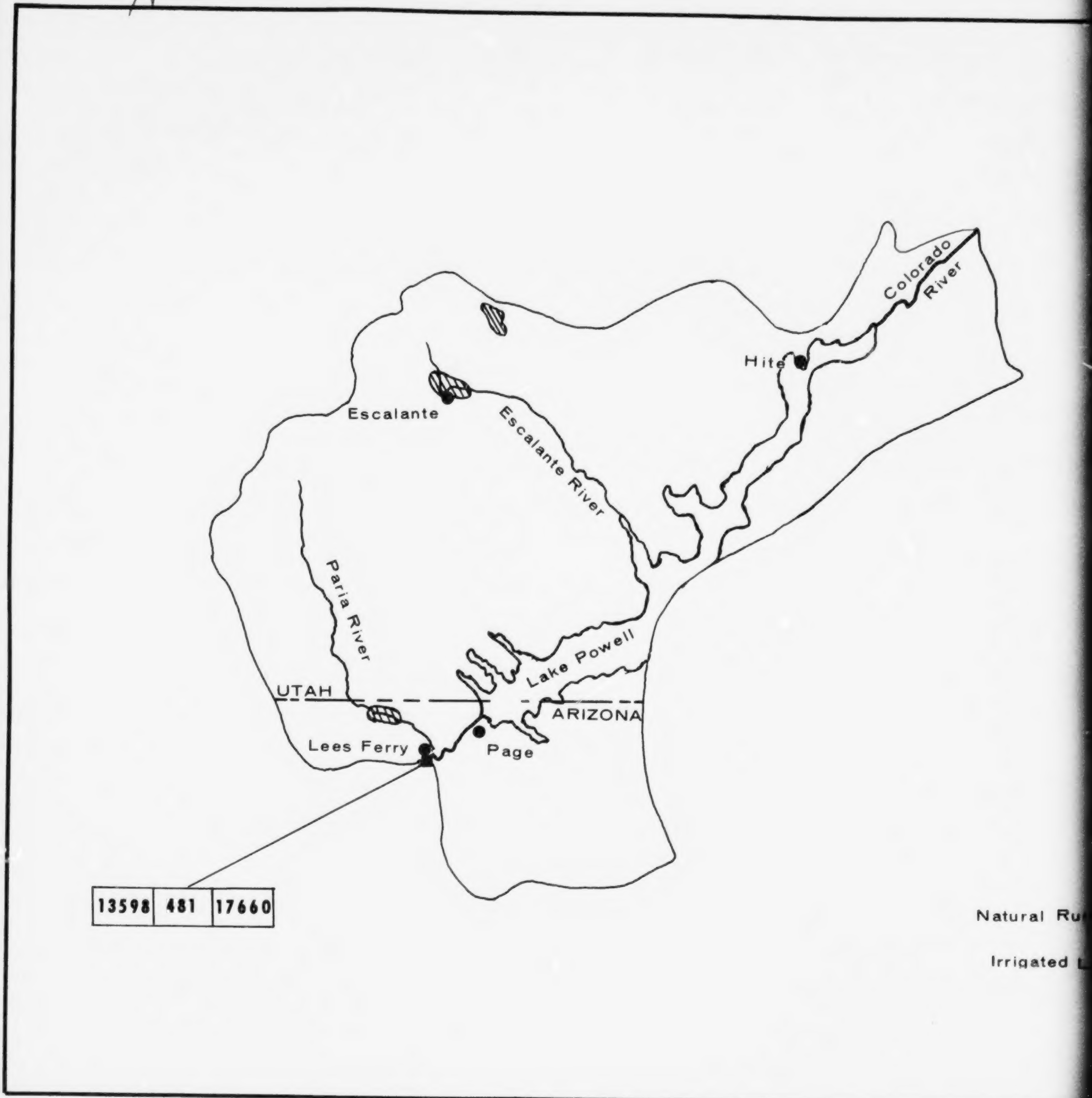
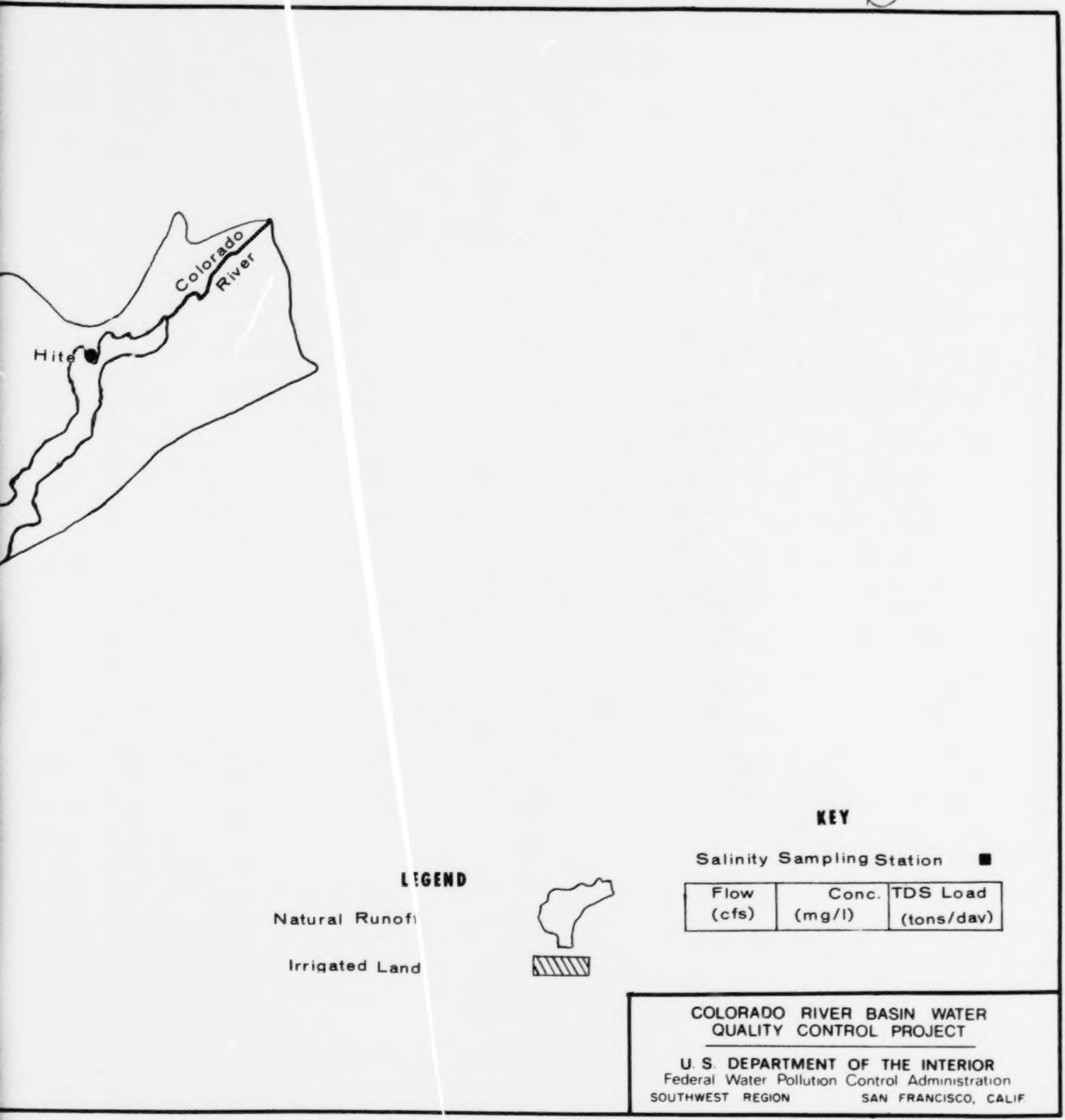

Colorado River
Hite
Escalante
Escalante River
Paria River
Lake Powell
UTAH
ARIZONA
Lees Ferry
Page
13598
481
17660
Natural Ru
Irrigated L

Figure 39 Flow and Quality at Key Sampling Stations and Location of Pri
in Study Area 26, Upper Colorado River Basin, 1965–66


Colorado
River
Hite
KEY
Salinity Sampling Station ■
Flow (cfs)
Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff
Irrigated Land
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
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mpling Stations and Location of Principal Salinity Sources
pper Colorado River Basin, 1965–66

La Plata drainage areas (Figure 40). The area encompasses 11,484 square miles in Hinsdale, Archuleta, Mineral, and La Plata Counties of Colorado; and Rio Arriba, Sandoval, McKinley, and San Juan Counties in New Mexico. Principal communities in the area and their 1960 populations include Pagosa Springs, Colorado (1,374); and Farmington, New Mexico (23,786).

The San Juan River and its tributaries head on the Continental Divide in the glaciated Rocky Mountains. Below Pagosa Springs, the streams flow on flat-lying sediments of the Colorado plateau. Elevations range from approximately 4,950 feet at Shiprock to more than 13,000 feet in the headwaters areas. Precipitation varies from less than 8 inches in the lowlands to more than 20 inches in the headwaters areas, with virtually all the streamflow being derived from a small portion of the area.

Description of Area 28. This area consists of the Animas and La Plata River drainage basins, which cover 1,340 square miles in San Juan and La Plata Counties in Colorado; and San Juan County in New Mexico. Principal communities in the area and their 1960 populations include Durango (10,530) and Silverton (822) in Colorado; and Aztec (4,137) in New Mexico. A portion of the city of Farmington, New Mexico, also lies within the Animas drainage. Elevations range from 5,400 feet at Farmington to more than 13,000 feet in the headwaters areas. Precipitation varies from less than 8 inches to over 20 inches per year, with the bulk of the runoff coming from the high mountains in Colorado.

Findings (Areas 27 and 28). Because of the complex system of water interchanges between Areas 27 and 28, they are considered together in the discussion of findings.

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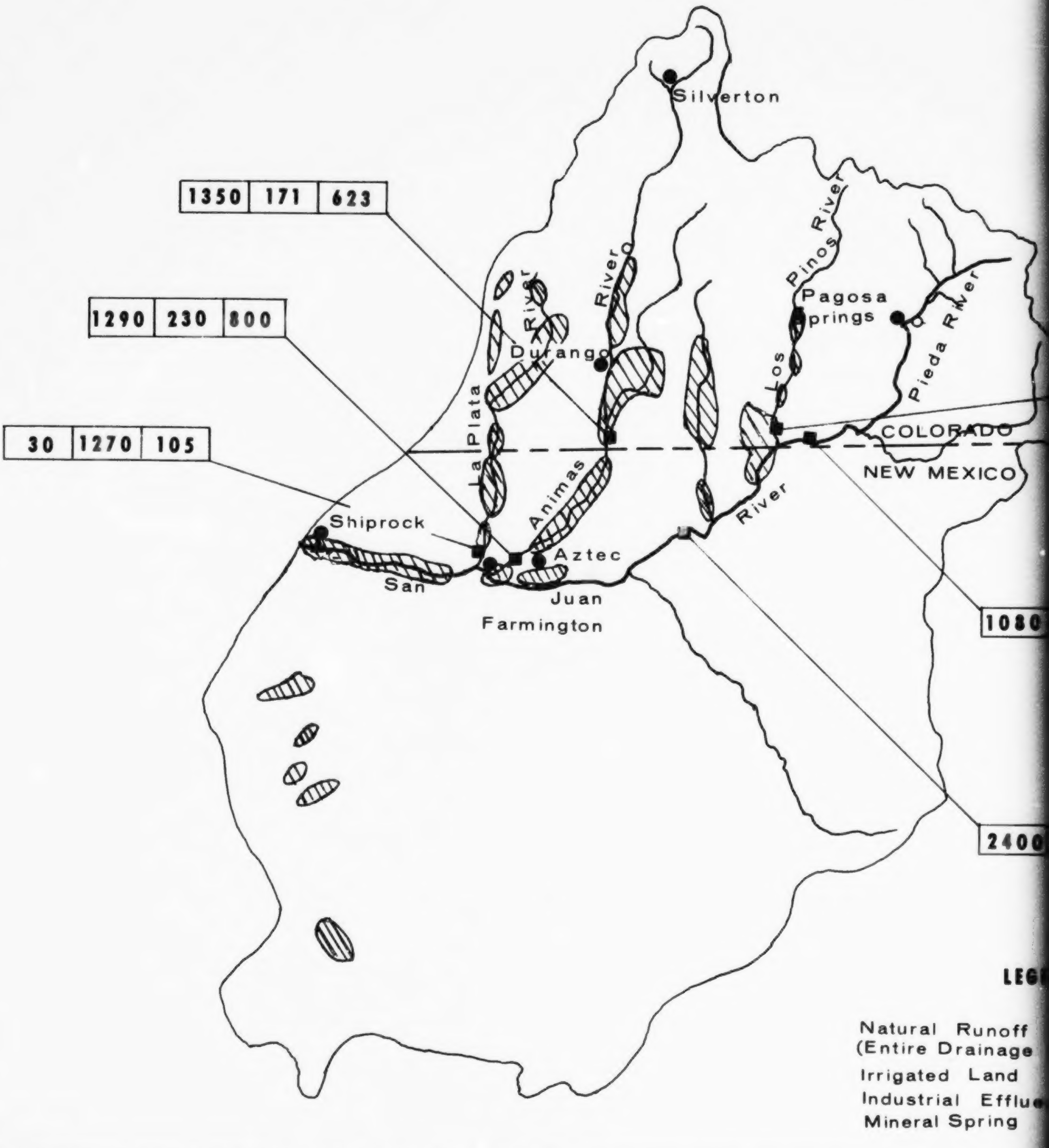
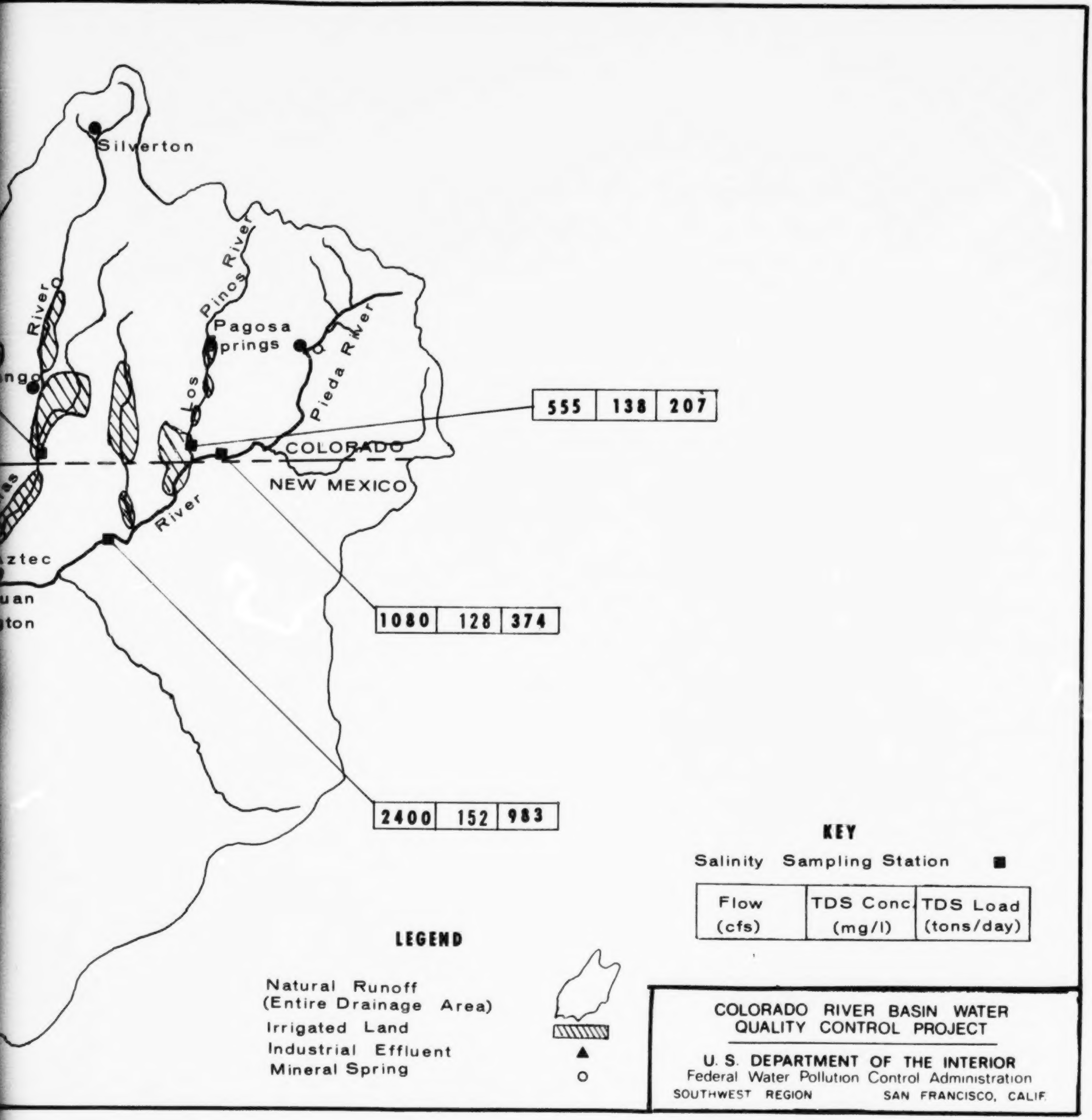


1350 171 623
1290 230 800
30 1270 105
1080
2400
Silverton
Durango
Pagosa Springs
Shiprock
Aztec
Farmington
La Plata River
Animas River
Los Pinos River
Piedra River
San Juan River
River
COLORADO
NEW MEXICO
LEG
Natural Runoff
(Entire Drainage
Irrigated Land
Industrial Efflue
Mineral Spring

Figure 40 Flow and Quality at Key Sampling Stations and Locat
in Study Areas 27 & 28. Upper Colorado


Silverton
River
Los Pinos River
Pagosa Springs
Piedra River
ngo
COLORADO
NEW MEXICO
River
Aztec
Juan
gton
555 | 138 | 207
1080 | 128 | 374
2400 | 152 | 983
KEY
Salinity Sampling Station ■
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land ▨
Industrial Effluent ▲
Mineral Spring ○
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF.

at Key Sampling Stations and Location of Principal Salinity Sources
ly Areas 27 & 28, Upper Colorado River Basin, 1965-66

Irrigation of approximately 12,000 acres above Pagosa Springs contributed a salt load of 3 to 4 tons per day to the San Juan River. This low average yield of 0.01 ton per acre per year indicates the insoluble nature of the formations underlying the irrigated areas. Mineral springs in the Pagosa Springs area yielded 2.3 cfs and 20 tons of salt per day to the San Juan River.

In the San Juan River reach, between Pagosa Springs and Carracas, Colorado, the mean annual increase in flow was 540 cfs and the salt load increase was 260 tons per day. Approximately 100 tons per day of this increase was due to irrigation of lands underlain by Mancos shale and Tertiary sediments, which are rich in soluble minerals.

Because of the complex interrelations between diversions and returns within the watersheds of the Animas River between Durango and Cedar Hill, and the Los Pinos and Florida Rivers, a water and salt budget was prepared for this entire area. During the study period, the mean salt load from irrigation in the area was only 33 tons per day, or an average yield of approximately 0.2 tons per acre per year. In the Animas River reach between Cedar Hill and Farmington mean annual flow was depleted by 60 cfs but the salt load increased 177 tons per day. Irrigation of approximately 17,000 acres along this reach added 165 tons of salt per day, or an average 3.5 tons per acre per year. Runoff from the area contributed 33 cfs and 12 tons of salt per day to the river.

The Animas River headwaters above Howardsville are of fair quality, with TDS concentrations of less than 300 mg/l. Cement [illegible]eek was badly polluted with mine drainage and products of natural sulfide oxidation.

The pH of the stream was approximately 4 and TDS concentration was greater than 1,000 mg/l during the study period. Much of this pollution was attributable to drainage from an active mine at the old town of Gladstone; however, drainage from other abandoned mines and tunnels added to the problem. Mineral Creek is also polluted by mine drainage, although to a lesser degree. During the study period, pH ranged from 4.6 to 7.1 and TDS concentrations were less than 400 mg/l.

The Animas River reach, below Baker's Bridge and upstream of Durango, had a salt-load increase of approximately 100 tons per day. Pinkerton Hot Springs, at the Golden Horseshoe Ranch, accounted for approximately 5 tons of salt per day of this total. Other small springs, including Trimble Hot Springs, contributed unknown amounts of salt to the stream. The remainder of the salt load within the reach may result from mineralized inflow into the stream directly from alluvium along the river.

Almost the entire flow of the La Plata River is consumed during the irrigation season. The allocation of water between Colorado and New Mexico is defined by the La Plata River Treaty. The mean annual flow of the La Plata River at its mouth during the study period was 30 cfs, and the salt load contributed was 105 tons per day. Irrigation of 15,000 acres in Colorado contributed 56 tons of salt per day, or an average yield of 1.4 tons per acre per year. Irrigation of 5,000 acres in New Mexico contributed 4 tons of salt per day, or an average yield of 0.3 tons per acre per year. The difference in salt yields from these areas is largely due to the presence of Mancos shale in the Colorado areas, and the less soluble formations underlying the New Mexico area.

Seepage from the tailings ponds at the Vanadium Corporation of America uranium mill at Shiprock added approximately 11 tons of salt per day to the San Juan River. Bottom ash and fly ash removal systems at the Four Corners Powerplant near Shiprock contributed a salt load of approximately 35 tons per day. The increase in total dissolved solids concentrations in the San Juan River, due to blowdown from the cooling systems, consumptive use, and discharge of minerals dissolved from fly ash and bottom ash, was 54 mg/l.

Chemical composition of all headwater streams in the study area were generally typical, except that proportions of sulfate were slightly higher due to irrigation in the headwater areas. Sulfate became predominant below the inflow from the La Plata River reflecting the effects of irrigation of gypsum-rich soils in the Colorado-New Mexico Border areas.

The salt budget for Study Areas 27 and 28 is given in the following tabulation.

Source	TDS Load (tons/day)	Percent of Total Load
Mine Drainage	15	1.0
Irrigation	362	24.0
Mineral Springs	25	1.7
Runoff	1,037	69.5
Municipal Effluents	10	.7
Industrial Effluent	46	3.1
Total	1,495	

Study Area 29 (San Juan Subbasin)

Description. Area 29 comprises the San Juan River drainage between Shiprock, New Mexico, and the San Juan arm of Lake Powell. It covers approximately 11,500 square miles and includes portions of Montezuma and Dolores Counties in Colorado; San Juan County of Utah; San Juan

County in New Mexico; and Apache and Navajo Counties in Arizona. Communities within the area and their 1960 populations include Cortez (6,764), Colorado; Bluff (100), Blanding (2,200), and Mexican Hat (250), Utah. The area downstream of Mexican Hat, Utah, is virtually inaccessible. Tributaries to the San Juan River include Mancos River, McElmo Creek, Navajo Springs Creek, and Chinle Wash. Elevations range from 4,000 feet to approximately 7,500 feet. Precipitation varies from less than 6 inches per year in the lowlands to approximately 16 inches per year along the northern boundary of the study area (Figure 41).

Area 29 is located in the flat-lying sediments of the Colorado Plateau. Streams are deeply incised, throughout most of the area, but ground-water is at such great depth that there is virtually no base flow to streams in the canyon areas. A principal tributary, the Mancos River, flows across the Mancos shale, dissolving salts from the formation, and degrading the stream. Other than during infrequent thunder storms, the only significant runoff originates in the uplands along the northern limits of the study area.

Findings. Flow in the San Juan River reach between Shiprock, New Mexico and Mexican Hat, Utah, increased by 240 cfs and the salt load increased by 2,490 tons per day during the study period. Much of the inflow is attributable to diversion from the Dolores River and subsequent irrigation and drainage in the McElmo Creek Basin. Intermittent tributary inflow within the reach conveyed approximately 650 tons of salt per day to the San Juan River. A major portion of this salt load was contributed by irrigation return flows, including water which originated upstream of the USGS gage on the San Juan River near Shiprock. Thus, it was not possible

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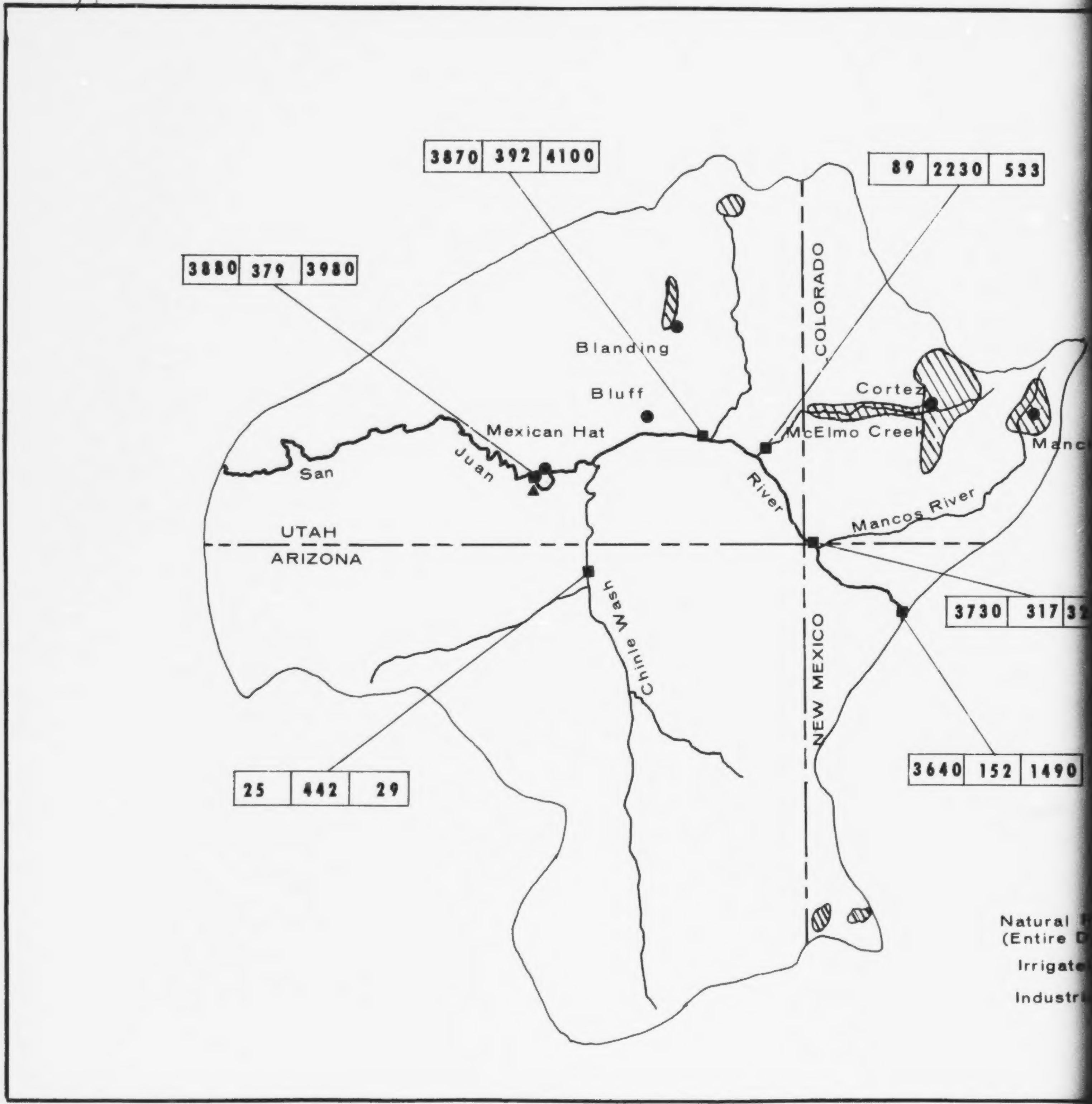
3870 | 392 | 4100
89 | 2230 | 533
3880 | 379 | 3980
COLORADO
Blanding
Bluff
Cortez
Mexican Hat
McElmo Creek
Manc
San
Juan
River
Mancos River
UTAH
ARIZONA
3730 | 317 | 32
Chinle Wash
NEW MEXICO
25 | 442 | 29
3640 | 152 | 1490
Natural F
(Entire D
Irrigate
Industri

Figure 41 Flow and Quality at Key Sampling Stations and Location of Pri
in Study Area 29, Upper Colorado River Basin, 1965–6

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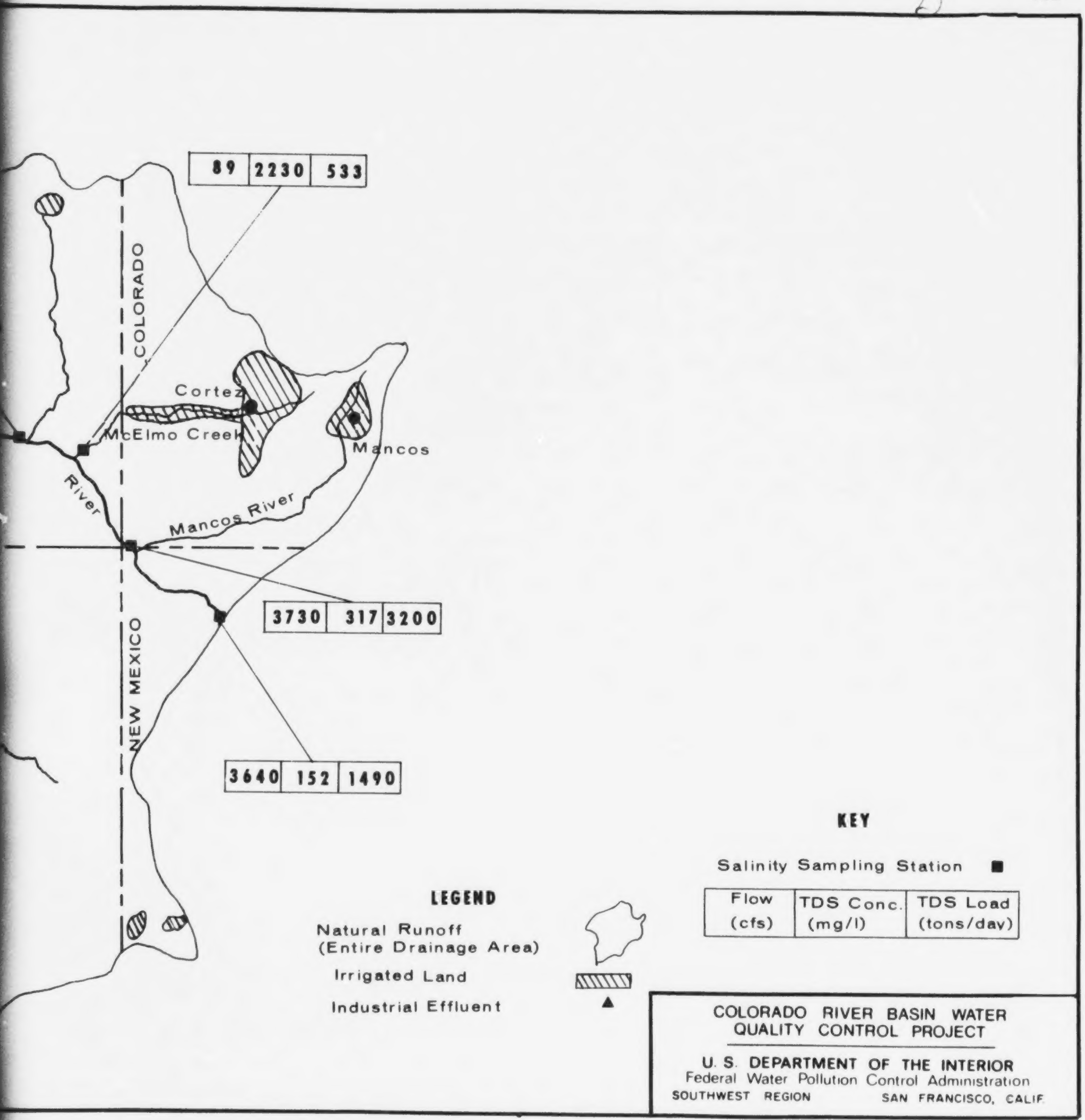
89 | 2230 | 533
COLORADO
Cortez
McElmo Creek
Mancos
River
Mancos River
3730 | 317 | 3200
NEW MEXICO
3640 | 152 | 1490
KEY
Salinity Sampling Station ■
Flow (cfs) | TDS Conc. (mg/l) | TDS Load (tons/dav)
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land ▨
Industrial Effluent ▲
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF.

Sampling Stations and Location of Principal Salinity Sources
Upper Colorado River Basin, 1965–66

to develop an accurate salt and water budget for the area. Within this reach, the Mancos River upstream of the mouth of Navajo Creek contributed a salt load of approximately 100 tons per day. Navajo Springs Creek discharged approximately 80 tons of salt per day, virtually all of which was attributable to irrigation return flow in the Cortez-Towaoc area. TDS concentrations in the Mancos River varied from 280 mg/l during spring runoff to a high of 1,580 mg/l during the winter months. The concentrations in Navajo Springs Creek ranged from 1,790 mg/l to 6,480 mg/l.

McElmo Creek yielded a mean annual flow of 89 cfs and a salt load of 533 tons per day. Most of the flow in McElmo Creek is derived from irrigation in the Cortez area which is supplied by water diverted from the Dolores River. Chinle Wash contributed a mean flow of 25 cfs and a salt load of 29 tons per day. Flowing oil-test holes in the Four Corners area contributed an additional 5 tons of salt per day to the San Juan River system.

The proportions of mineral constituents remained essentially the same throughout the San Juan River reach in Area 29.

RESULTS OF FIELD INVESTIGATIONS - LOWER BASIN

A brief description of the Lower Colorado River Basin and the significant findings of the Project's field studies in the Lower Basin are presented in this section.

Description

For the purpose of this Appendix, the Lower Colorado River Basin consists of the drainage area directly tributary to the Colorado River from Lees Ferry near the Arizona-Utah state line to the Southerly International Boundary, excluding the upper reaches of the drainage areas of the Little Colorado and Gila Rivers. The tributary areas include lands in southwestern Utah, southern Nevada, southeastern California, and northern and western Arizona. Principal communities and their 1960 population are Las Vegas (170,000),[1] Henderson (12,525), and Boulder City (4,058), Nevada; Kanab (1,645) and St. George (5,130), Utah; Kingman (4,525) and Yuma (23,974), Arizona; Needles (4,540) and Blythe (6,023), California. Numberous other small settlements and resort communities are located along the Colorado River between Davis Dam and Yuma.

Principal tributaries include Kanab Creek, Bright Angel Creek, Havasu Creek, the Virgin River, Muddy River, and the Bill Williams River. Throughout the Colorado Plateau portion of the Basin, the Colorado River flows through the Grand Canyon. The western and southern portions of the Basin are within the Basin and Range Province and are made up of a series of fault block and volcanic mountains separated by valleys filled to great depths with alluvium. The climate of the Basin varies widely from near Alpine conditions in the mountainous areas to true desert conditions in the lowlands along the lower reaches of the Colorado River. Annual precipitation ranges from less than 5 inches in the lower Colorado River area to more than 20 inches along the North Rim of the Grand Canyon. Only small portions of the Lower Colorado River Basin yield significant amounts of runoff.

Evaporation has a major effect on mineral quality in many areas of the Lower Colorado River Basin. Evaporation from lakes and reservoirs exceeds 6 feet annually in many areas. The concentrating effect of transpiration by the large areas of phreatophyte growth along the streams also has a major influence on mineral quality of water.

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[1] Includes metropolitan area outside city limits, but does not include visitor population.

Owing to low precipitation and high evaporation, the lowlands yield almost no runoff except during intense storms. Soluble minerals in the soil profile are leached out and discharged to streams during the infrequent runoff events.

Findings.

Lees Ferry to Hoover Dam. Flow and salt load in the reach of the Colorado River between Lees Ferry and Grand Canyon, Arizona, increased by 460 cfs and 2,310 tons per day during the study period. The flow and salt load contributed by various sources within this reach are given in the following tabulation (Figure 42).

Source	Flow (cfs)	TDS (mg/l)	Salt Load (tons/day)
Paria River at Lees Ferry	18.1	880	43
Little Colorado River at Cameron	209	780	439
Moenkopi Wash near Cameron	27.3	1,490	110
Blue Springs at mouth of Little Colorado River	222	2,500	1,500
Miscellaneous Springs	14.0		10
Total	490.4		2,102

Ionic composition within the reach was essentially constant throughout the study area (Figure 50).

Between the Grand Canyon station and Hoover Dam it is not possible to balance flow since there is no flow measurement on the Colorado River near its entrance to Lake Mead. If evaporation from the lake could be accurately quantified, ungaged flow into the lake could be calculated

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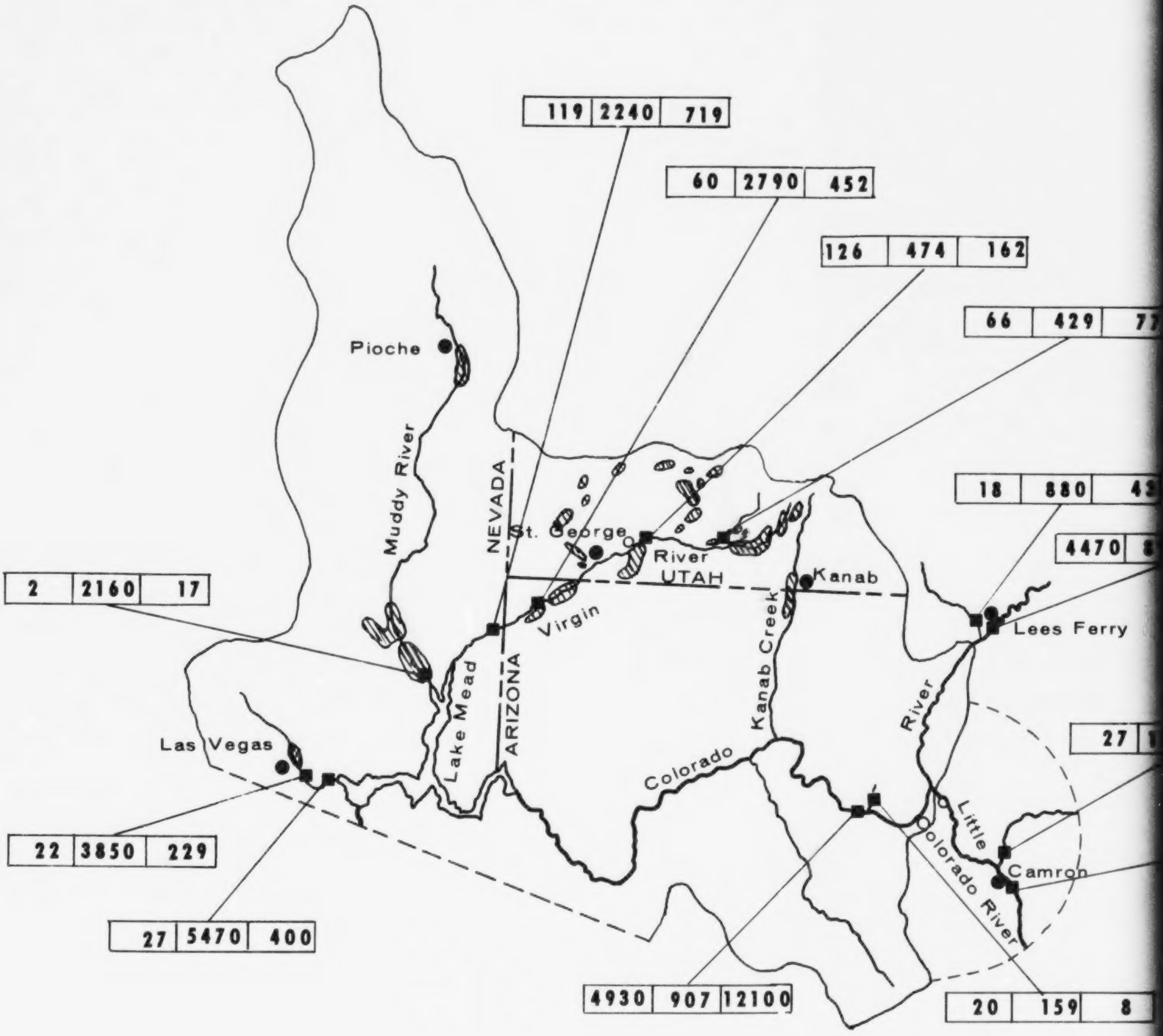
119 | 2240 | 719
60 | 2790 | 452
126 | 474 | 162
66 | 429 | 77
18 | 880 | 45
4470 | 8
2 | 2160 | 17
Pioche
Muddy River
NEVADA
St. George
River
UTAH
Kanab
Virgin
Lees Ferry
Lake Mead
ARIZONA
Kanab Creek
River
Las Vegas
Colorado
27 | 1
Little
Colorado River
Camron
22 | 3850 | 229
27 | 5470 | 400
4930 | 907 | 12100
20 | 159 | 8

Figure 42 Flow and Quality at Key Sampling Stations and Location of Princ
Between Lees Ferry and Hoover Dam, Lower Colorado River

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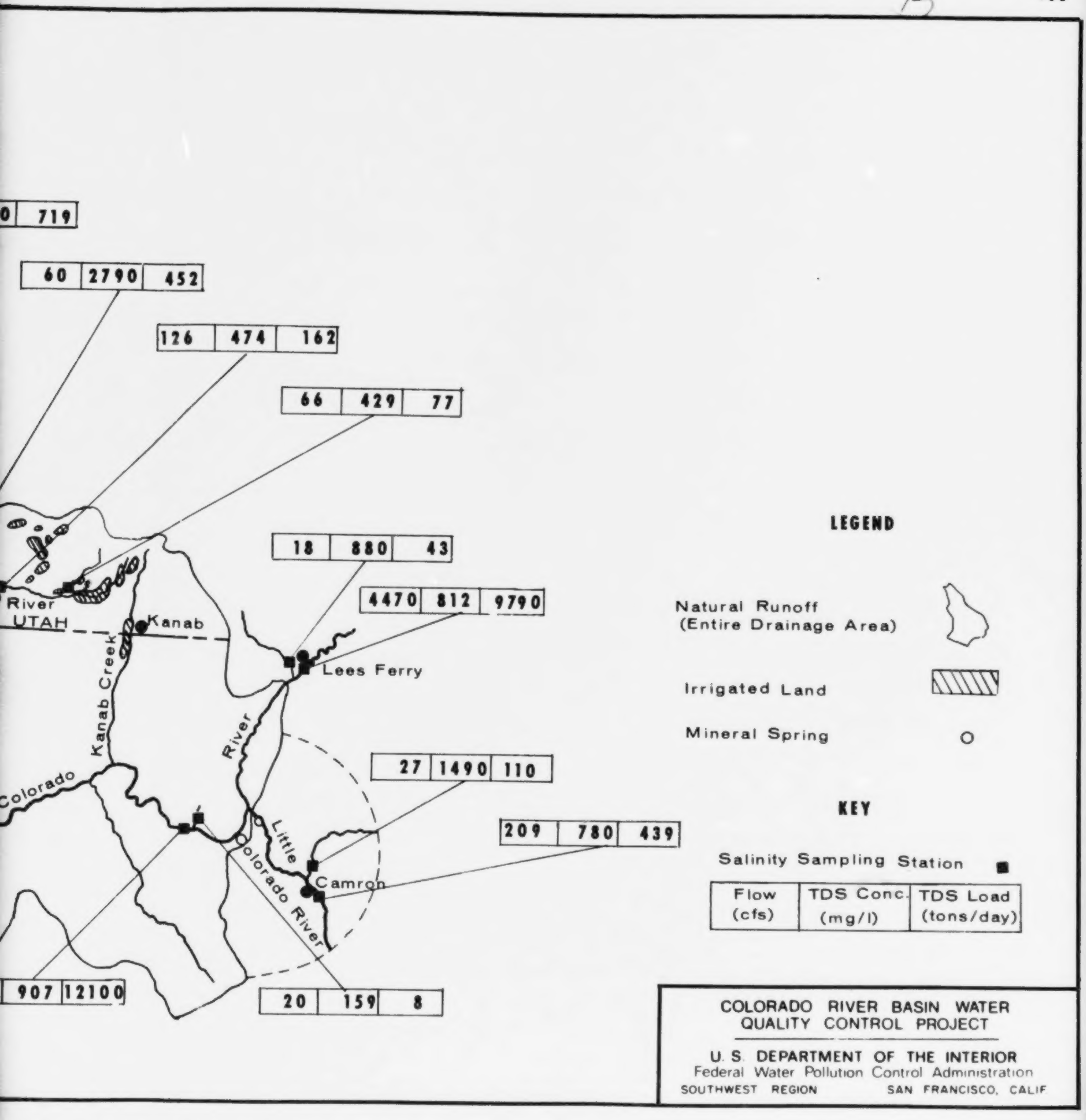
719
60 | 2790 | 452
126 | 474 | 162
66 | 429 | 77
18 | 880 | 43
4470 | 812 | 9790
27 | 1490 | 110
209 | 780 | 439
907 | 12100
20 | 159 | 8
River
UTAH
Kanab
Kanab Creek
Lees Ferry
River
Little
Colorado River
Colorado
Camron
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land
Mineral Spring
KEY
Salinity Sampling Station
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF

Sampling Stations and Location of Principal Salinity Sources
and Hoover Dam, Lower Colorado River Basin, 1964

from evaporation losses and the sum of flows from the Grand Canyon gaging station and the intervening tributaries. Water and salt sources within the reach are shown in the following tabulation.

Source	Flow (cfs)	TDS (mg/l)	Salt Load (tons/day)
Bright Angel Creek	20	159	8
Tapeats Creek	80	120	26
Kanab Creek	12	1,180	38
Havasu Creek	70	352	66
Vulcan or Lava Falls Spring	6	750	10
Approx. 18 misc. springs	26		21
Virgin River at Riverside	60	2,790	452
Muddy River at mouth	2	3,160	17
Rogers Spring	2	3,200	17
Las Vegas Wash	27	5,470	400
Total	305		1,055

The headwaters of the North Fork of the Virgin River in Zion National Park yielded 66.3 cfs and 77 tons of salt per day. In the stream reach between Springdale and Virgin, Utah, flow increased by 60 cfs and salt load increased by 85 tons per day. These increases were attributable to ungaged inflow from the East Fork of the Virgin River and irrigation of small parcels of land in the Rockville, Springville, and Virgin areas.

In the reach of the Virgin River between Virgin, Utah, and Littlefield, Arizona, mean annual flow decreased by 7 cfs and salt load increased by 557 tons per day. Two major springs add salt and water to the Virgin

River within this reach. One of these, LaVerkin Springs, is located along both banks and in the channel of the Virgin River, immediately upstream of the trace of the Hurricane Fault, at LaVerkin, Utah. The discharge from this spring is of a sodium-sulfate-chloride composition and add 286 tons of salt per day to the system, as well as highly significant quantities of radioactive elements. The second spring, located at Littlefield, may not be an additional source since it is possible that it represents the reappearance of water which is lost from the Virgin River into the cavernous bedrock in Virgin Canyon between St. George and Littlefield. Irrigation of approximately 18,000 acres within the reach added a salt load of 112 tons of salt per day to the system, or an average salt yield of 2.3 tons per acre per year.

In the reach of the Virgin River between Littlefield, Arizona, and Riverside, Nevada, flow decreased by 59 cfs and the salt load decreased by 267 tons per day. These decreases in flow and load indicate that salt was stored in the irrigated areas during the study period.

Chemical composition of the Virgin River was not characteristic of headwaters streams (Figure 50). Calcium and bicarbonate were predominant, with concentrations of sodium and chloride nearly as high. Slight increases in the proportions of calcium and sulfide were observed at the sampling station at Virgin, Utah. At Littlefield the chemical composition of the Virgin River was significantly altered by the irrigation returns near St. George, Utah, and by the inflow from springs at LaVerkin and Littlefield. Sulfate and chloride concentrations increased sharply and all cations increased in approximately equal proportions. Additional consumptive use and irrigation return flows in the Littlefield and Mesquite areas caused increases in all mineral constituents in approximately equal proportions.

Essentially the entire flow of the Muddy River was utilized consumptively in the irrigation of approximately 9,000 acres. Another 10,000 acres in the area are irrigated by ground-water. Mean flow and salt load discharged at the most downstream station on the Muddy River was 2 cfs and 17 tons per day during the study period. The sampling station near the point of inflow to Lake Mead was situated such that considerable amounts of seepage from irrigation may not have been measured.

Chemical composition of the Muddy River at Glendale was predominantly calcium-sodium-sulfate reflecting the character of runoff from this area. Near the mouth of the Muddy River, sulfate and chloride became the predominant anions, and each of the principal cations increased.

Except during infrequent storms, flow in Las Vegas Wash is made up entirely of municipal and industrial effluent, seepage from industrial waste ponds, irrigation return flow, and outflow from an artificially recharged near-surface aquifer. During the period of study, mean annual flow and salt load measured at the USGS gage near Henderson, Nevada, was 22 cfs and 229 tons per day. The mean TDS concentration was 3,850 mg/l. At the mouth of Las Vegas Wash, mean flow was 27 cfs, mean salt load was 400 tons per day and the mean TDS concentration was 5,470 mg/l. Thus, an increase of 5 cfs and 171 tons per day occurred between the two stations. Since there were no surface inflows between these two stations, the increase in flow resulted in flow of ground-water which is not measured at the upstream gage. A natural bedrock sill below the gage apparently forces water moving in the aquifer upward into the stream increasing the

the surface flow at the mouth of the Wash. Discharge measurements at the two stations subsequent to the year of study indicate that the inflow between the two stations has increased to as much as 8 cfs.

Increases in individual mineral constituents between the two sampling staions on Las Vegas Wash were essentially proportional.

The salt budget for the reach of the Colorado River between Lees Ferry and Hoover Dam is given in the following tabulation.

Source	TDS Load (tons/day)	Percent of Average Load
Springs	1,990	58.0
Irrigation	112	3.3
Municipal	43	1.3
Runoff	1,282	37.4
Total	3,427	

Hoover Dam to Southerly International Boundary. The mean flows, TDS concentrations and salt loads at stations within this reach are shown in the following tabulation (Figure 43).

Location of Station on Colorado River	Flow (cfs)	TDS (mg/l)	TDS Load (tons/day)
Below Hoover Dam	11,430	721	21,860
Below Davis Dam	11,190	726	21,930
Below Parker Dam	9,290	723	18,130
Below Palo Verde weir	7,470	732	14,760
At Blythe-Ehrenberg Bridge	7,610	755	15,510
Below Cibola Valley	8,280	822	18,380

The causes of changes in flow and salt load between each of the stations are discussed briefly in the following sections. More detailed discussions of these changes are included in an open file report available at the Project Office in Denver, Colorado.

The increase in TDS concentration between Hoover Dam and Davis Dam is due to evapotranspiration by phreatophytes and inflow from saline

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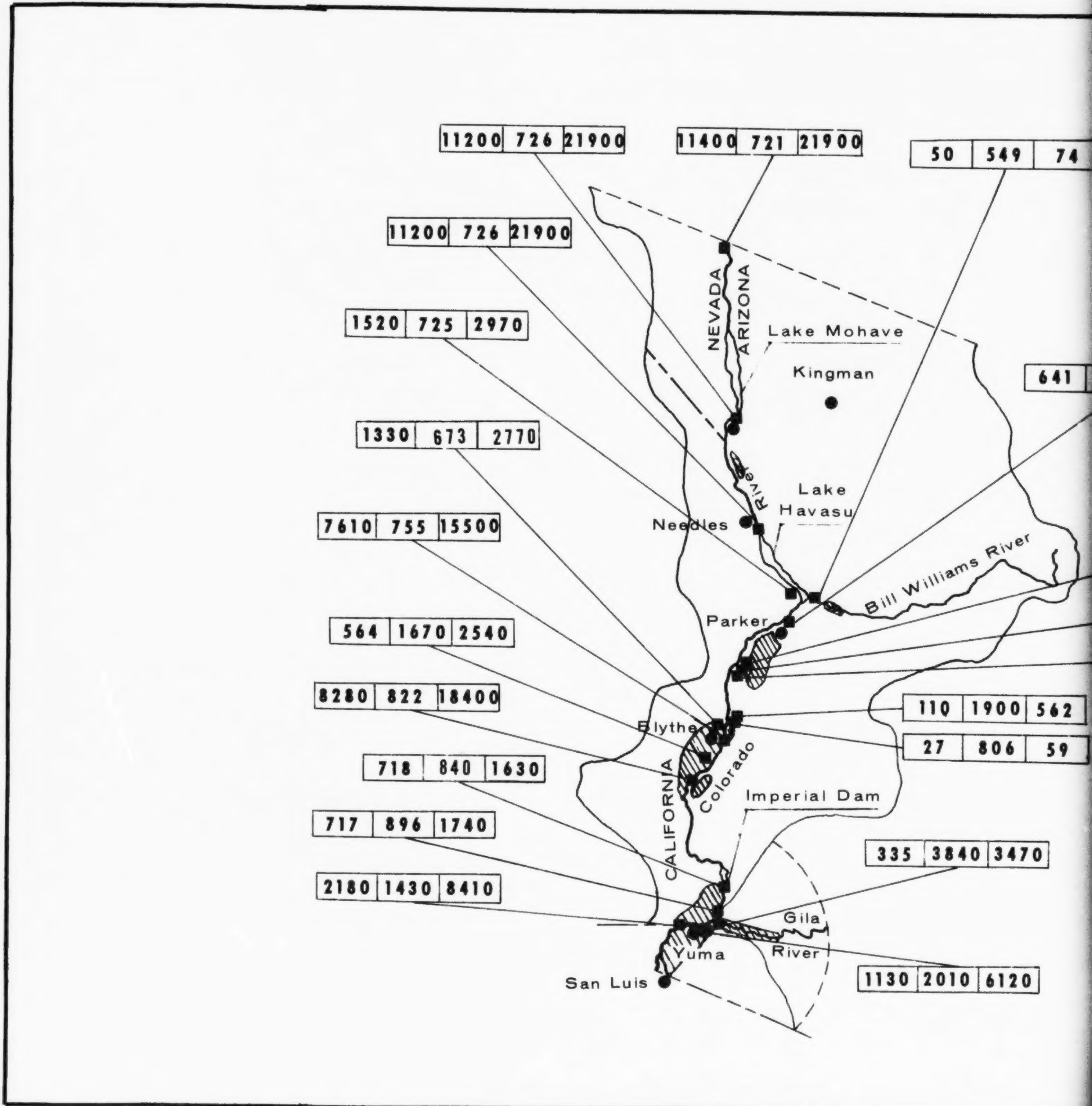
11200 | 726 | 21900
11400 | 721 | 21900
50 | 549 | 74
11200 | 726 | 21900
1520 | 725 | 2970
641
1330 | 673 | 2770
7610 | 755 | 15500
564 | 1670 | 2540
8280 | 822 | 18400
110 | 1900 | 562
27 | 806 | 59
718 | 840 | 1630
717 | 896 | 1740
335 | 3840 | 3470
2180 | 1430 | 8410
1130 | 2010 | 6120
NEVADA
ARIZONA
Lake Mohave
Kingman
River
Lake
Havasu
Needles
Bill Williams River
Parker
Blythe
Colorado
CALIFORNIA
Imperial Dam
Gila
River
Yuma
San Luis

Figure 43 Flow and Quality at Key Sampling Stations and Location of Pr
Below Hoover Dam, Lower Colorado River Basin, 196

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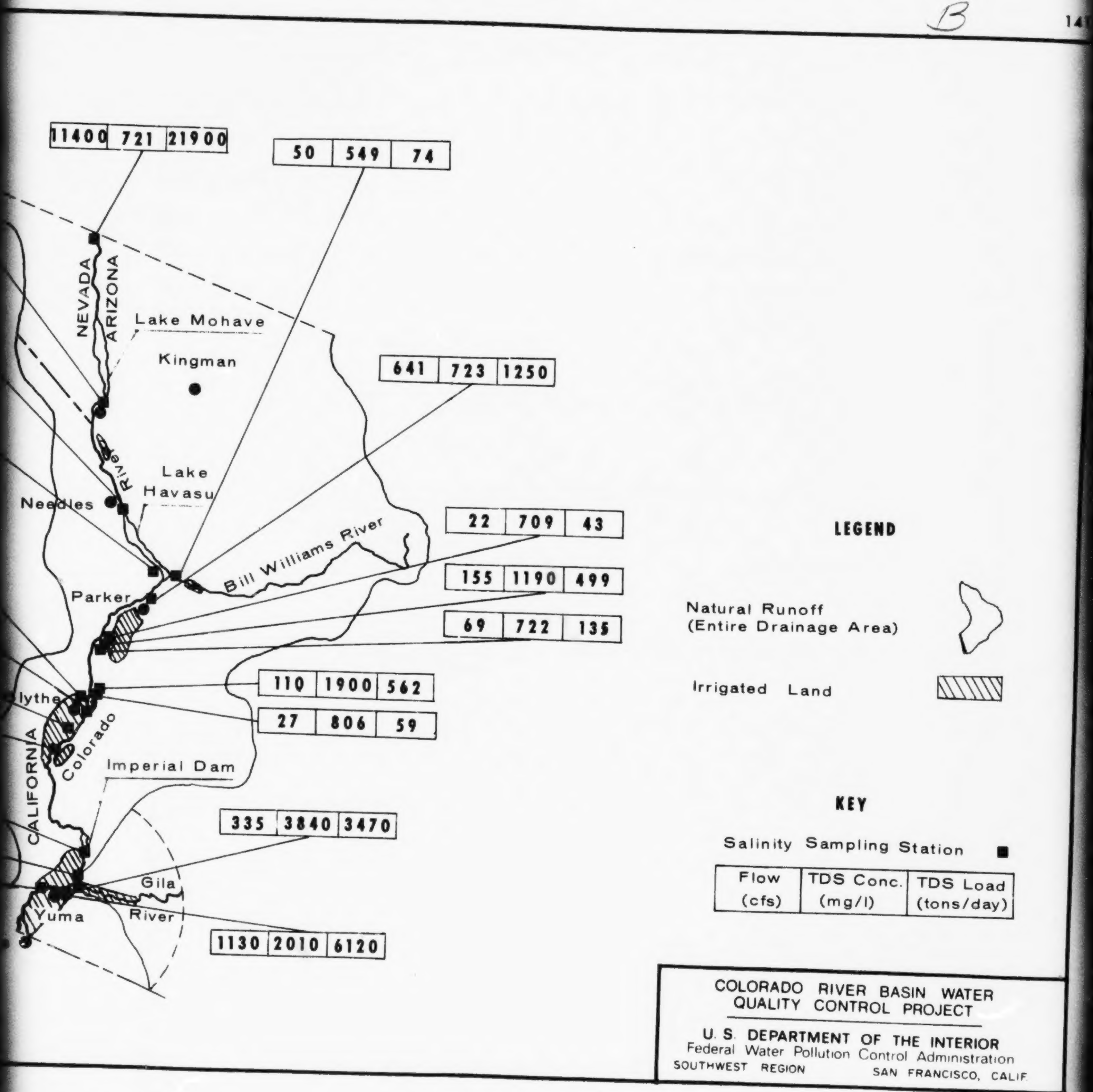

11400 | 721 | 21900
50 | 549 | 74
NEVADA
ARIZONA
Lake Mohave
Kingman
641 | 723 | 1250
River
Lake Havasu
Needles
22 | 709 | 43
Bill Williams River
155 | 1190 | 499
Parker
69 | 722 | 135
110 | 1900 | 562
lythe
27 | 806 | 59
CALIFORNIA
Colorado
Imperial Dam
335 | 3840 | 3470
Gila River
Yuma
1130 | 2010 | 6120
LEGEND
Natural Runoff (Entire Drainage Area)
Irrigated Land
KEY
Salinity Sampling Station
Flow (cfs)
TDS Conc. (mg/l)
TDS Load (tons/day)
COLORADO RIVER BASIN WATER QUALITY CONTROL PROJECT
U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF.

Key Sampling Stations and Location of Principal Salinity Sources
ver Dam, Lower Colorado River Basin, 1963–64

springs below Willow Beach. The decrease in flow is well within the range of accuracy of flow measurement at the two stations, but may actually reflect some losses due to the phreatophyte growth within the reach.

In the river reach between Davis Dam and Parker Dam, the Metropolitan Water District of Southern California (MWD) diverted 1520 cfs and 2770 tons of salt per day during the study period. The analytical methods employed by MWD in determining TDS concentrations at Parker Dam utilized a calculation of the sum of the constituent ions which caused the reported concentration to be slightly lower than that at upstream and downstream stations. On the basis of residue concentrations, the diverted load was on the order of 3,000 tons per day. Municipal discharge from Needles, California, added 1 cfs and 4 tons of salt per day. The Bill Williams River discharged a mean flow of 50 cfs at a TDS concentration of 549 mg/l and contributed 74 tons of salt per day to the river system. The salt load contributed by the Bill Williams River was virtually all from natural sources. During the study period, water levels in Lake Mohave and Lake Havasu increased as additional water was stored. It is estimated that decreases in flow due to evaporation and bank storage within the reach totaled 620 cfs during the study period. Bank storage of salt load was estimated at 724 tons per day. The additional losses of 60 cfs and 110 tons of salt per day were apparently caused by the increase in storage in Lake Mohave and Lake Havasu during the study period.

Between Parker Dam and Imperial Dam there are no major flowing tributaries and no significant discharges of salt loads from natural sources.

The Colorado River Indian Reservation (CRIR) on the Arizona side of the river near Parker, Arizona, and the Palo Verde Irrigation District (PVID) in California near the town of Blythe, returned irrigation drainage, spillage of excess water from canals, and groundwater from drainage wells to the Colorado River.

The CRIR, with 31,940 acres under irrigation, consumed 187,300 acre-feet of water and contributed a salt load of 48 tons per day or an average of 0.5 tons per acre per year.

The Palo Verde Irrigation District, with approximately 84,300 acres under irrigation, consumed 366,000 acre-feet of water and contributed a salt load of 492 tons per day, an average of 2.1 tons per acre per year. Much of the salt addition from the Palo Verde Irrigation District resulted from lowering of the groundwater table by deepening of existing drains which resulted in removal of salt previously stored in the irrigated area. With adequate drainage, the salt yield from PVID would be expected to approximate that from the Colorado River Indian Reservation. Irrigation of a small area in Cibola Valley may also contribute some salt load to the Colorado River through diffuse seepage.

A summation of the salt loads and discharge gains and losses between Parker Dam and Imperial Dam revealed a loss of 242 cfs and a salt load gain of 100 tons per day. Calculations indicate that transpiration from 41,600 acres of phreatophyte growth and evaporation from the 9,600 acres of free water surface within the reach consumed 240,000 acre-feet of water during the year of study. Ungaged inflow within the reach, due to seepage from irrigated areas, was calculated at 60,000 acre-feet. Local precipitation and runoff contributed 13,000 acre-feet. The ungaged inflow of 73,000 acre-feet plus the previously cited loss in flow over the reach totaled 258,000 acre-feet. This approximated the calculated losses due to evapotranspiration.

Chemical composition of the Colorado River in the reach between Parker Dam and Imperial Dam reflected the inflow of drainage from irrigated areas having high sodium and chloride concentrations (Figure 50). The chemical composition of drainage from the Upper Main Drain on the CRIR had the same relative proportions as water of the Colorado River but all concentrations were slightly higher. Drainage from the Lower Main Drain on the CRIR was predominantly sodium-chloride-sulfate type water. These observations are in keeping with the history of irrigation development on the CRIR. Lands drained by the Upper Main Drain have been irrigated for a number of years and are well leached. Some of the lands drained by the Lower Main Drain were receiving initial leaching during the period of study. Sodium, chloride, and sulfate were predominant in drainage water from the Palo Verde Irrigation District. As indicated earlier, the higher TDS concentrations were related to the deepening of drains within that area.

Of the 8,280 cfs and 18,770 tons of salt per day reaching Imperial Dam during the study period, 718 cfs and 1,630 tons per day continued down the Colorado River channel; 1,240 cfs and 2,810 tons per day were diverted into the Gila Main Gravity Canal; and 6,320 cfs and 14,330 tons were diverted into the All American Canal.

Between Imperial Dam and the Northerly International Boundary, flow and salt load in the river increased by 1,460 cfs and 6,780 tons per day. These increases were attributable to numerous canal and irrigation returns to the river. The measured contributions are summarized in the following tabulation.

Source	Discharge (cfs)	TDS Load (tons/day)
Laguna Canal Wasteway	5.7	14
Levee Canal Wasteway	17.6	40
North Gila Drain	11.2	44
Gila River (incl. Wellton-Mohawk Drainage as well as South and North Gila Valley	335	3,470
Yuma Main Canal Wasteway	117	265
Reservation Drain No. 4	62.7	196
Drain 8-B	4.7	12
Pilot Knob Wasteway	806	1,830
Total	1,359.9	5,871

It is emphasized that the above tabulation lists gross returns to the river. Net measured changes in flow and salt load due to irrigation within the reach were a depletion of 1,160 cfs and an addition of 530 tons per day. Domestic use of water at Yuma added a salt load of 17 tons per day to the reach. The totals in the tabulation leave an unaccounted ungaged increase in flow of 100 cfs and increase in salt load of 910 tons per day. These increases are believed to be mainly due to seepage from intensive irrigation within the reach although some of the increase may be due to normal errors in flow measurements and laboratory analyses on the many measured returns shown in the tabulation.

Subsequent to completion of the Project's studies in the Lower Basin, the Wellton-Mohawk Main Outlet Drain was extended to the Northerly International Boundary where the Mexican government exercises the option of accepting the highly saline water above or below Morelos Dam.

No attempt was made to develop water and salt budgets for the Colorado River downstream of the Northerly International Boundary. Return flows to the Colorado River include the Cooper Wasteway which returned 5 tons of salt per day; the 11-Mile Wasteway, returning 28 tons of salt per day; and the 21-Mile Wasteway, discharging 19 tons of salt per day. The Yuma Project Valley Division Main Drain and the East Main Canal join at the Southerly International Boundary and cross into Mexico at San Luis Sonora. The Main Drain discharged 187 cfs and 796 tons of salt per day, and the East Main Canal discharged 12.2 cfs and 40 tons of salt per day during the study period. In summary, discharges at the Northerly International Boundary returns to the Limatrophe Section, and discharges at the Southerly International Boundary totaled 2,400 cfs with a salt load of 9,300 tons per day during the study period.

Chemical composition of the Colorado River, between Imperial Dam and the Northerly International Boundary, became predominantly sodium, chloride, and sulfate as a result of the highly saline inputs from the lower Gila River and the Wellton-Mohawk Irrigation District (Figure 50). Extension of the Wellton-Mohawk Main Outlet Drain to the Northerly Border has ameliorated this unfavorable condition in the immediate reach of the Colorado River.

SUMMARY OF FINDINGS FOR ENTIRE COLORADO RIVER BASIN

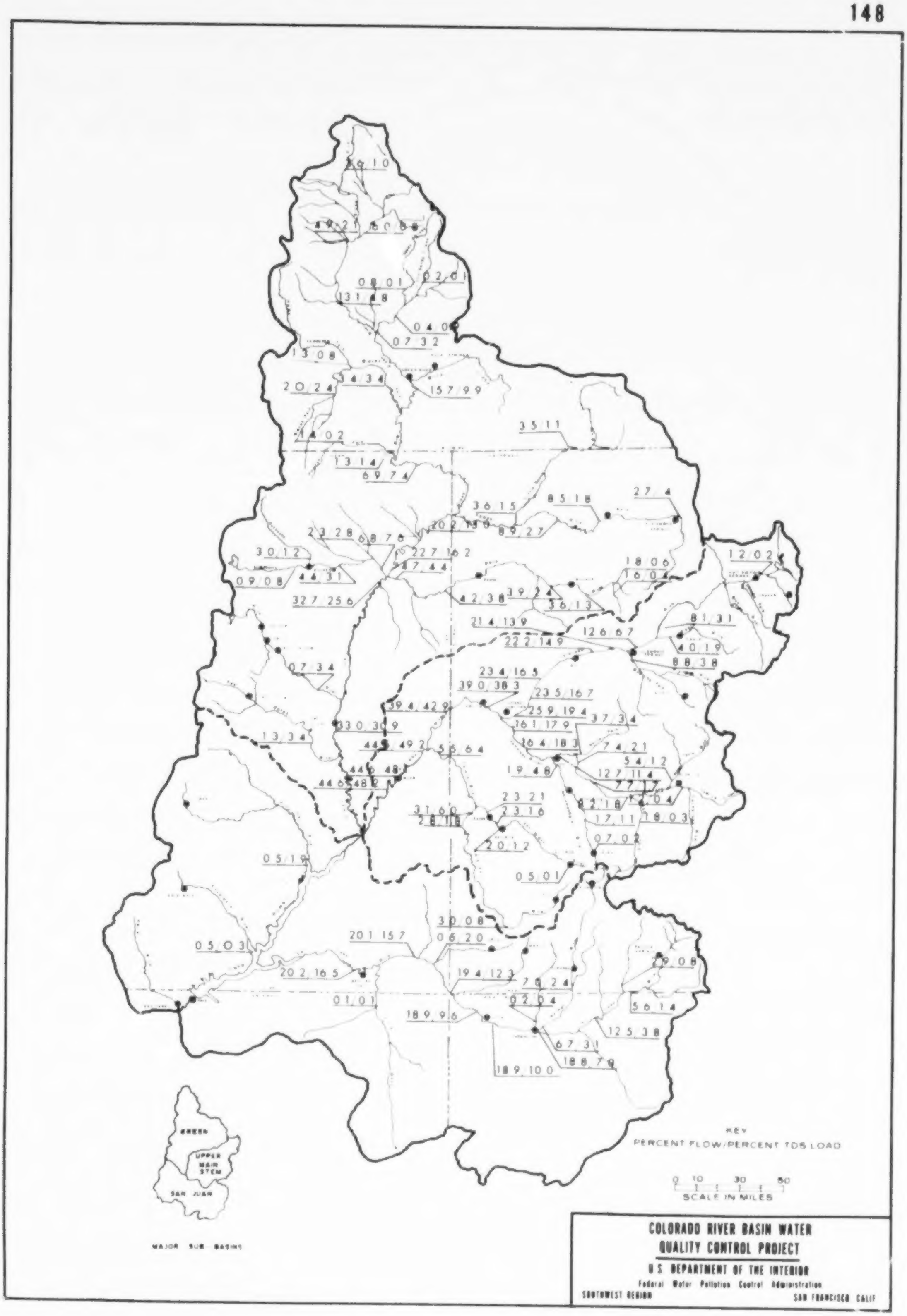
During the period June 1965 through May 1966, the mean annual flow from the Upper Colorado River Basin was 19,263 cfs. The salt load discharged into Lake Powell during the same period averaged 26,160 tons per day. The flow and salt load contributed by each of three major subbasins is shown in the following tabulation.

Subbasin	Flow cfs	Flow Percent of Upper Basin Outflow	Salt Load Tons/day	Salt Load Percent of Upper Basin Outflow
Upper Main Stem	8,582	44.5	12,587	48.1
Green River	6,600	34.3	9,020	34.5
San Juan River	4,081	21.2	4,553	17.4
Total	19,263		26,160	

The percentage of total Upper Basin mean daily flow and salt load passing key stations is shown in Figure 44.

Runoff, including both overland runoff and groundwater inflow to streams, contributed 52 percent of the salt load from the Upper Colorado River Basin. The mountainous headwaters areas, consisting of insoluble rocks of highly resistant outcrops, yielded large quantities of good quality water. The lower valley areas, composed of more soluble sediments, contributed small amounts of highly mineralized water. It became clear that contact of water with the saline geologic formations of the Upper Basin, whether from natural precipitation or from irrigation, caused serious degradation of water quality in the streams receiving runoff or drainage from these formations.

In the Lower Colorado Basin, consumptive use of water greatly exceeded inflow to the river system and salt sources within the Basin added an estimated 5,484 tons per day to the stream system. Approximately three-fourths of the salt load and virtually all of the flow in the Lower Colorado Basin was discharged from the Upper Basin. The relative magnitudes of salt loads contributed by various types of sources in the Colorado River Basin are summarized graphically in Figure 45. The percentage of Lower Basin flow and load passing key sampling stations is shown in Figure 46.


3 6/1 0
4 9/2 1
6 0/0 6
0 8/0 1
0 2/0 1
13 1/4 8
0 4/0 9
0 7/3 2
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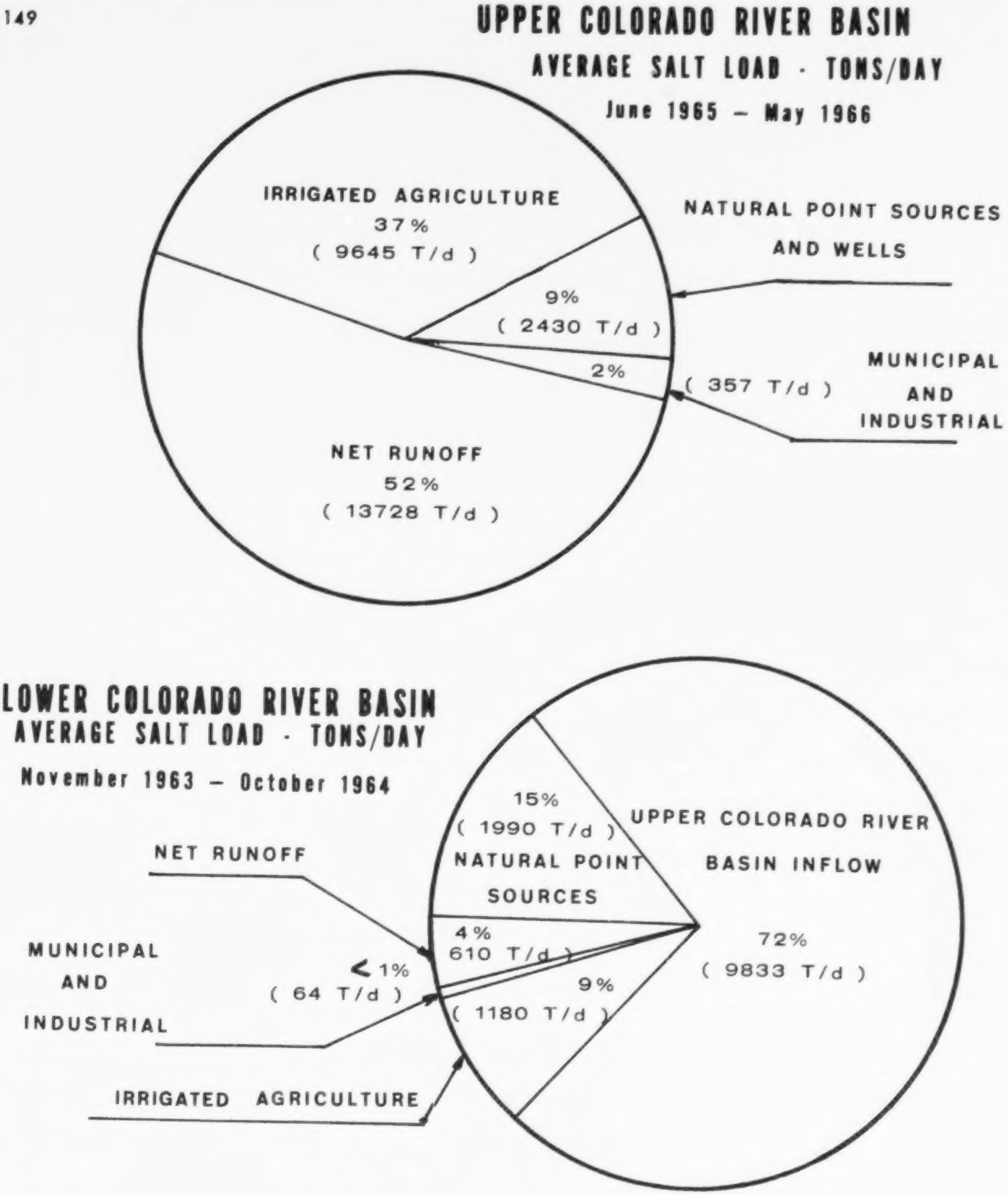
2 0/2 4
3 4/3 4
15 7/9 9
1 4/0 2
1 3/1 4
6 9/7 4
3 5/1 1
3 6/1 5
8 5/1 8
2 7/ 4
20 2/15 0
8 9/2 7
2 3/2 8
6 8/7 8
3 0/1 2
22 7/16 2
4 7/4 4
0 9/0 8
4 4/3 1
32 7/25 6
1 2/0 2
1 8/0 6
1 6/0 4
4 2/3 8
3 9/2 4
3 6/1 3
21 4/13 9
12 6/6 7
22 2/14 9
8 1/3 1
4 0/1 9
8 8/3 8
0 7/3 4
23 4/16 5
39 0/38 3
23 5/16 7
39 4/42 9
25 9/19 4
16 1/17 9
3 7/3 4
33 0/30 9
1 3/3 4
44 5/49 2
5 5/6 4
16 4/18 3
7 4/2 1
5 4/1 2
44 5/48 1
1 9/4 8
12 7/11 4
44 6/48 2
7 7/1 7
2 3/2 1
3 1/6 0
2 3/1 6
2 8/1 8
8 2/1 8
1 2/0 4
17 1/1
1 8/0 3
2 0/1 2
0 7/0 2
0 5/1 9
0 5/0 1
3 0/0 8
0 5/0 3
20 1/15 7
0 6/2 0
2 9/0 8
20 2/16 5
19 4/12 3
7 6/2 4
0 1/0 1
0 2/0 4
5 6/1 4
18 9/9 6
12 5/3 8
6 7/3 1
18 8/7 9
18 9/10 0
GREEN
UPPER MAIN STEM
SAN JUAN
MAJOR SUB BASINS
KEY
PERCENT FLOW/PERCENT TDS LOAD
0 10 30 50
SCALE IN MILES
COLORADO RIVER BASIN WATER
QUALITY CONTROL PROJECT
U.S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO CALIF

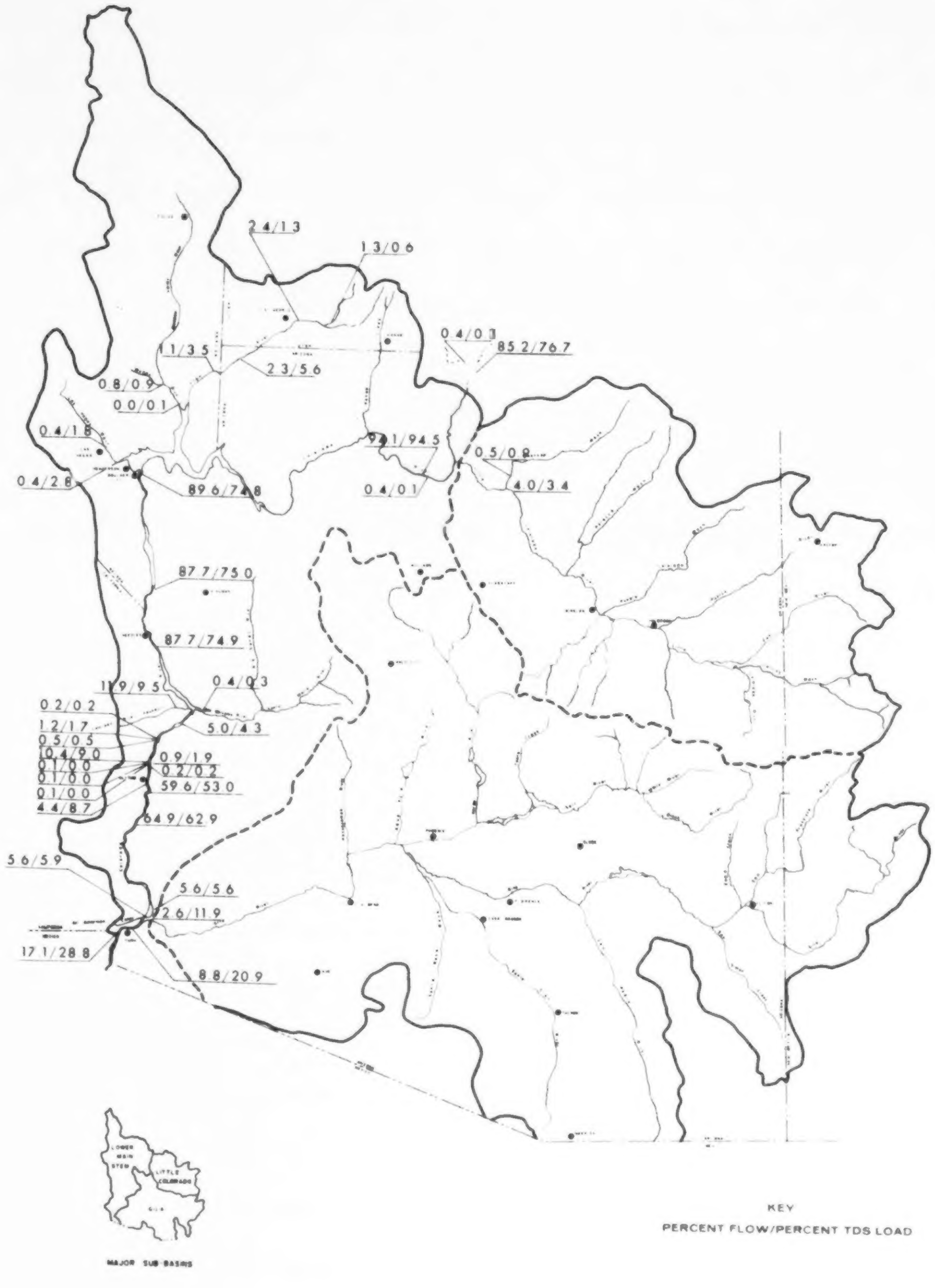
Figure 44 Percent of Average Daily Flow and TDS Load Entering Lake Powell,1965-66



UPPER COLORADO RIVER BASIN
AVERAGE SALT LOAD - TONS/DAY
June 1965 – May 1966

LOWER COLORADO RIVER BASIN
AVERAGE SALT LOAD - TONS/DAY
November 1963 – October 1964

Figure 45 Relative Magnitude of Salt Sources in the Colorado River Basin


2.4/1.3
1.3/0.6
1.1/3.5
2.3/5.6
0.4/0.3
85.2/76.7
0.8/0.9
0.0/0.1
0.4/1.8
0.4/2.8
89.6/74.8
94.1/94.5
0.4/0.1
0.5/0.8
4.0/3.4
87.7/75.0
87.7/74.9
11.9/9.5
0.4/0.3
0.2/0.2
1.2/1.7
0.5/0.5
5.0/4.3
10.4/9.0
0.9/1.9
0.1/0.0
0.2/0.2
0.1/0.0
59.6/53.0
0.1/0.0
4.4/8.7
64.9/62.9
5.6/5.9
5.6/5.6
2.6/11.9
17.1/28.8
8.8/20.9
LOWER MAIN STEM
LITTLE COLORADO
GILA
MAJOR SUB-BASINS
KEY
PERCENT FLOW/PERCENT TDS LOAD

COLORADO RIVER BASIN WATER
QUALITY CONTROL PROJECT
U.S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION **SAN FRANCISCO, CALIF**

Figure 46 Percent of Average Daily Flow and Load Entering the Colorado River below Lees Ferry, 1963-64

Irrigation contributed 37 percent of the salt load produced in the Upper Colorado River Basin. The salt load contributions and average salt yields from the major irrigated areas in the three subbasins are given by Table 5. Salt load contributions from the major irrigated areas in the Colorado River Basin are compared graphically in Figure 47.

Irrigation adjacent to the reach of the Colorado River between Hoover Dam and the Southerly International Boundary caused a net depletion of 1928 cfs in the Colorado River, and a net salt load addition to the stream of 1068 tons per day during the study period. The relative salt yields from these areas are summarized in Table 6. The range of salt load yields from the principal irrigated areas in the Colorado River Basin is shown in Figure 48.

Point sources such as springs, wells, and abandoned oil-test holes, contributed 10 percent of the salt load in the Upper Basin. The significant point sources of salinity and their respective salt loads are given in Table 7.

Springs added more salt load to the Lower Colorado River Basin than any other type of source. The measured contribution was nearly 2,000 tons of salt per day. Blue Springs, located near the mouth of the Little Colorado River, contributed a salt load of approximately 1,500 tons per day, constituting the largest single point source in the Colorado River Basin. Salt load contributions by major point sources are compared in Figure 49.

Municipal and industrial effluents added only about one percent of the Upper Basin salt load. Salt inputs from oil-field activities were found to be transitory in nature, and may at times, contribute considerably more or less salt to the system than was observed during the study. The

Table 5. Salt Yields and Loads From Irrigation In Green River Subbasin

Area	Salt Load (Tons/Day)	Average Salt Yield (Tons/Acre/Yr)
Green River above New Fork River	30	0.1
Big Sandy Creek	200	5.6
Blacks Fork in Lyman area	475	2.4
Hams Fork	6	0.3
Henry's Fork	244	4.9
Yampa River above Steamboat Springs	20	0.2
Yampa River, Steamboat Springs to Craig	24	0.4
Milk Creek	6	1.0
Williams Fork River	13	0.3
Little Sanke above Dixon	15	0.3
Little Sanke, Dixon to Baggs	25	0.5
Ashley Creek	230	4.2
Duchesne River	1350	3.0
White River below Meeker	20	2.0
Price River	580	8.5
San Rafael River	290	2.9
Total	3,528	
Percent of Green River Subbasin Salt Load	39.2	
Percent of Total Upper Basin Salt Load	13.5	

Table 5 (Cont'd.). Salt Yields and Loads From Irrigation In Upper Main Stem Subbasin

Area	Salt Load (Tons/Day)	Average Salt Yield (Tons/Acre/Yr)
Main Stem above Hot Sulphur Springs	15	0.3
Main Stem, Hot Sulphur Springs to Kremmling	61	0.9
Muddy Creek Drainage Area	46	2.4
Brush Creek	10	0.7
Roaring Fork River	200	3.5
Colorado River Valley, Glenwood Springs to Silt	100	2.3
Colorado River, Silt to Cameo	30	3.5
Grand Valley	1,925	8.0
Plateau Creek	75	0.9
Gunnison River above Gunnison	9	0.3
Tomichi Creek above Parlin	6	0.3
Tomichi Creek, Parlin to mouth	6	0.3
Uncompahgre above Dallas Creek	74	4.5
Lower Gunnison	3,000	6.7
Naturita Creek near Norwood	46	2.8
Total	5,603	
Percent of Upper Colorado River Subbasin Salt Load	44.5	
Percent Total of Upper Basin Salt Load	21.5	

Table 5 (Cont'd.). Salt Yields and Loads From Irrigation In San Juan River Subbasin

Area	Salt Load (Tons/Day)	Average Salt Yield (Tons/Acre/Yr)
Fremont River above Torrey, Utah	20	0.4
Fremont River, Torrey to Hanksville, Utah	16	5.8
Muddy Creek above Hanksville, Utah	60	3.1
San Juan above Carracas	104	2.7
Florida, Los Pinos, Animas drainage	33	0.2
Lower Animas Basin	165	3.5
LaPlata River in Colorado	56	1.4
LaPlata River in New Mexico	4	0.3
Total	518	
Percent of San Juan Subbasin Salt Load	12.9	
Percent Total of Upper Basin Salt Load	1.9	

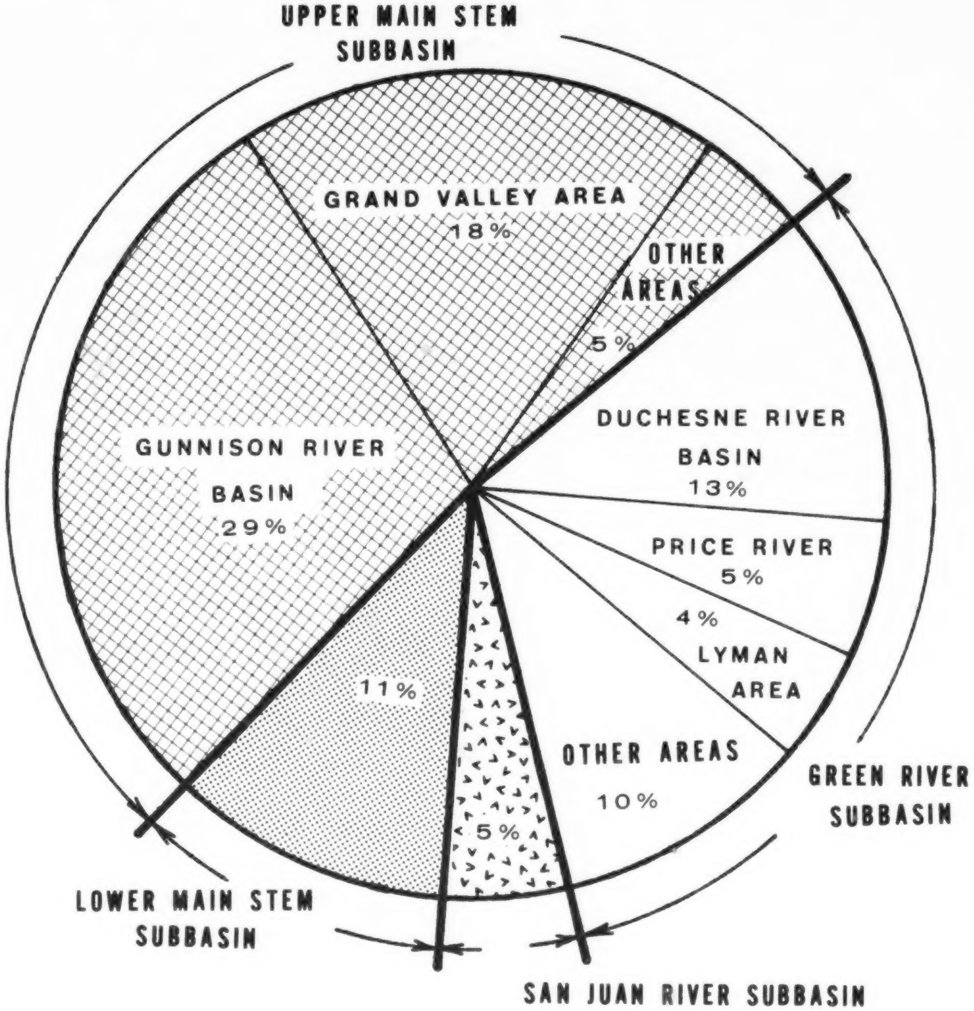


Figure 47 Relative Salt Loads from Irrigated Areas in Colorado River Basin

Table 6. Salt Yields and Loads From Irrigation In Lower Colorado River Basin

Area	Salt Load (Tons/Day)	Average Salt Yield (Tons/Acre/Yr)
Virgin River	112	2.3
Colorado River Indian Reservation	48	0.5
Palo Verde Irrigation District	490	2.1
Below Imperial Dam (Gila and Yuma Projects)	530	Variable
Total	1,180	

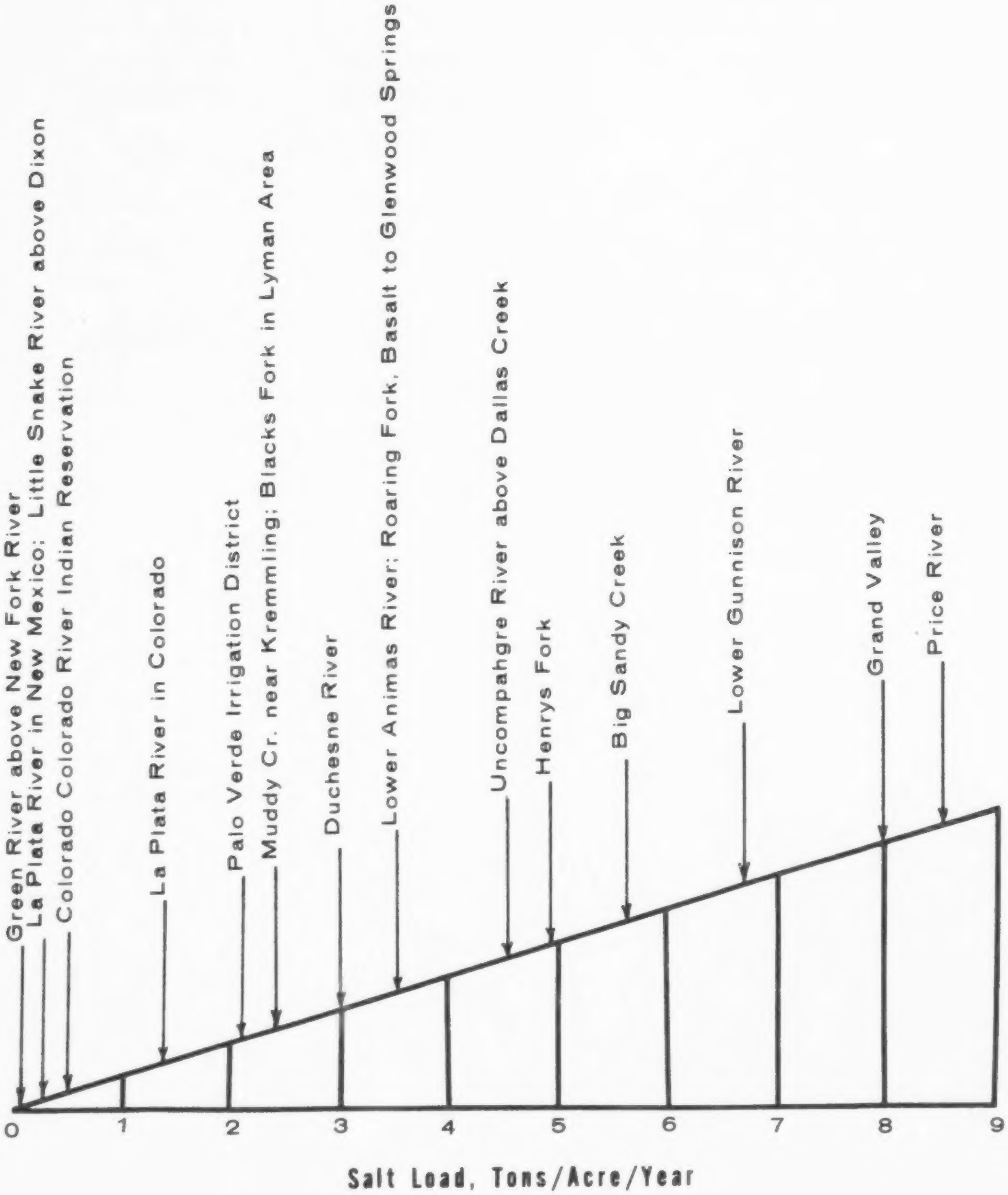


Figure 48 Observed Range of Salt Yields from Irrigated Areas in the Colorado River Basin

Table 7. Salt Load Contributions From Major Point Sources in Colorado River Basin

Source	Salt Load (Tons/Day)
Green River Subbasin	
Warm Kendall Spring	18
Cold Kendall Spring	8
Coal Mine Drainage near Oak Creek, Colorado	6
Steamboat Springs Mineral Springs	24
Jones Hole Creek-Whirlpool Canyon	21
Split Mountain Warm Springs	51
Test Hole near Jensen, Utah	1
Stinking Spring	1
Indian Creek Springs	3
Meeker Oil Test Hole	160
Piceance Creek Well	17
Crystal Geyser	53
Total	363
Upper Main Stem	
Hot Sulphur Springs	0
Dotsero Spring	440
Glenwood Springs Area	920
Ouray Hot Springs	4
Ridgeway Hot Springs	7
Paradise Hot Spring	2
Paradox Valley	688
Total	2,061
San Juan Subbasin	
Pagosa Hot Springs	20
Pinkerton Hot Spring	5
Total	25
Lower Colorado River Basin	
Blue Springs	1,500
Miscellaneous small springs above Grand Canyon	10
Vulcan or Lava Falls Spring	10
Miscellaneous springs above Virgin River	21
Havasu Spring	65
LaVerkin Spring	286
Littlefield Salt Springs	81
Rogers Spring	17
Total	1,990

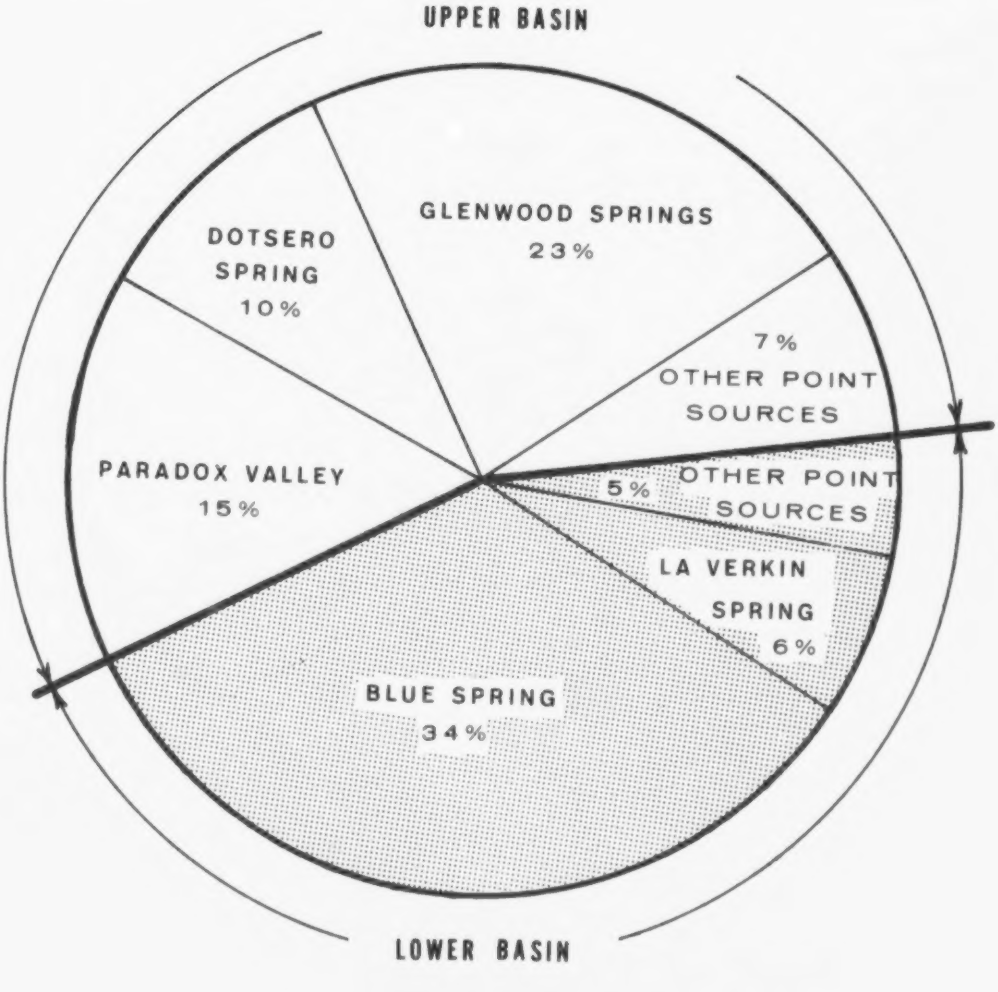


Figure 49. Comparison of Salt Loads from Point Sources in the Colorado River Basin

principal industrial and oil-field sources and their observed yields, are shown in Table 8.

Municipal and industrial waste discharges added 64 tons of salt per day to the Lower Colorado River. Seepage from ponds containing municipal and industrial wastes contributed a portion of the 400 tons per day input from Las Vegas Wash.

Headwater areas of streams in the Upper Basin, with few exceptions, yield predominantly calcium-bicarbonate type water. The use of these waters for irrigation of well-leached soils in upland areas did not seriously alter the chemical composition of the streams. Leaching of saline sediments in the lower valleys caused the waters to become predominantly sodium-calcium-sulfate type, in stream reaches below such areas where precipitation and/or applied irrigation water came into contact with these geological formations. The Mancos shale, the Paradox formation, and various saline Tertiary-age lakebed formations had the most serious effect on the chemical composition of streams. The effects of major springs and industrial effluents were discerned in the chemical composition of small receiving streams, but were essentially masked in the larger streams. Figures 51, 52, and 53 show the chemical composition of streams at key sampling stations in the Upper Basin.

The relative proportions of chemical constituents remained surprisingly consistent in the Lower Colorado River between Lee's Ferry and the mouth of the Gila River (Figure 50). Drainage containing predominantly calcium-sodium-sulfate-chloride type waters was discharged from newly irrigated lands on the lower portion of the Colorado River Indian Reservation, and from newly deepened drains in the Palo Verde Irrigation

Table 8. Salt Loads From Principal Industrial Sources, Colorado River Basin

Source	Salt Load (Tons/Day)
Green River Subbasin	
Flood Wash near Wellington, Utah	13
Iles Dome Oil Field water, Colorado	17
Ashley Valley Oil Field water, Utah	32
Total	62
Upper Main Stem	
New Jersey Zinc tailings decant, Gilman, Colorado	10
Union Carbide uranium mill effluent, Rifle, Colorado	40
Climax uranium mill effluent, Grand Junction, Colorado	35
American Gilsonite refinery effluent, Fruita, Colorado	9
Union Carbide uranium mill effluent, Uravan, Colorado	119
Atlas Mineral Corporation uranium mill effluent, Moab, Utah	36
Total	249
San Juan Subbasin	
Four Corners Power Plant, Shiprock, New Mexico	35
Foote Mineral Corporation uranium mill effluent Shiprock, New Mexico	11
Total	46

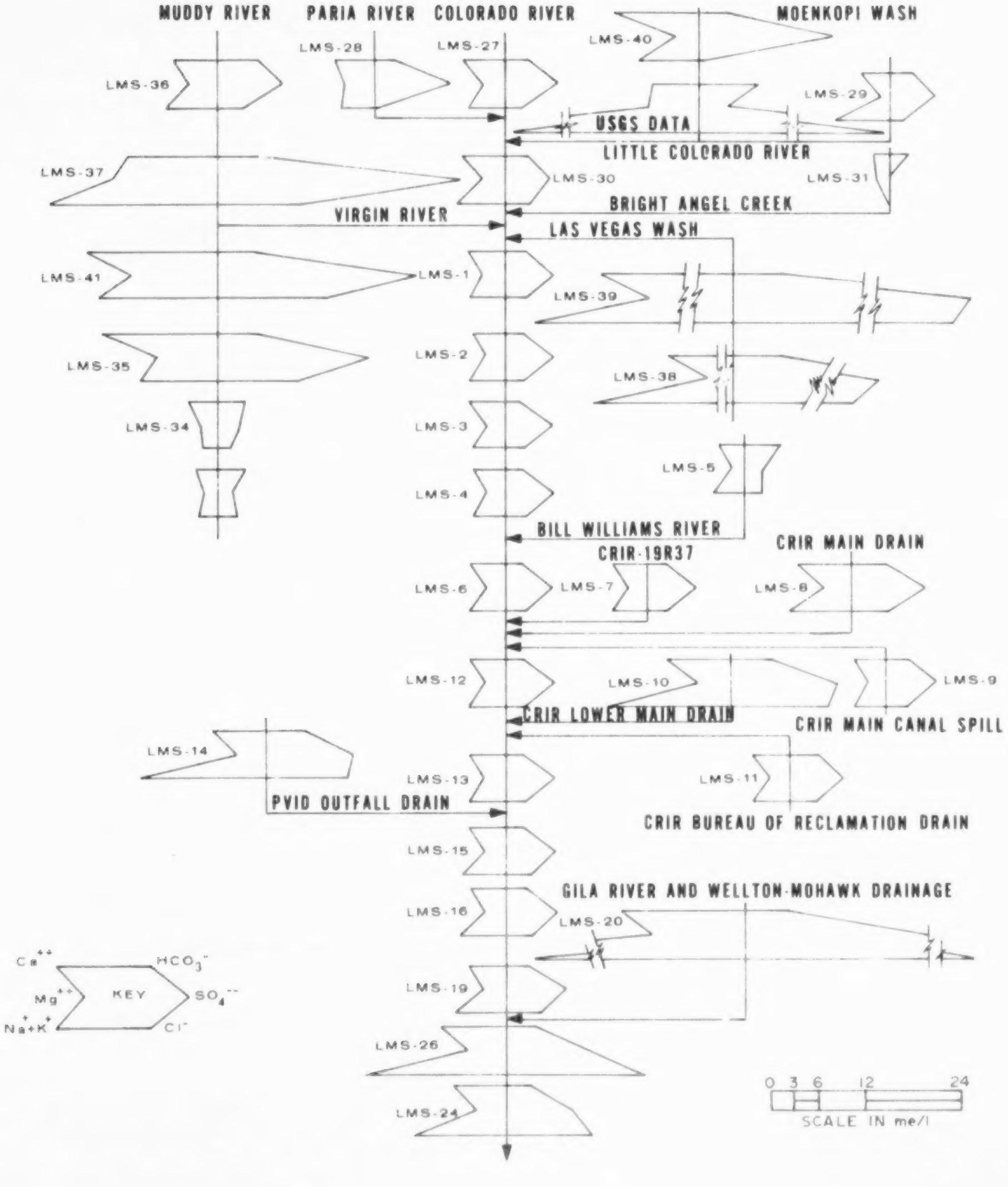

MUDDY RIVER
PARIA RIVER
COLORADO RIVER
MOENKOPI WASH
LMS-40
LMS-28
LMS-27
LMS-36
LMS-29
USGS DATA
LITTLE COLORADO RIVER
LMS-37
LMS-30
LMS-31
BRIGHT ANGEL CREEK
VIRGIN RIVER
LAS VEGAS WASH
LMS-41
LMS-1
LMS-39
LMS-35
LMS-2
LMS-38
LMS-34
LMS-3
LMS-5
LMS-4
BILL WILLIAMS RIVER
CRIR-19R37
CRIR MAIN DRAIN
LMS-6
LMS-7
LMS-8
LMS-12
LMS-10
LMS-9
CRIR LOWER MAIN DRAIN
CRIR MAIN CANAL SPILL
LMS-14
LMS-13
LMS-11
PVID OUTFALL DRAIN
CRIR BUREAU OF RECLAMATION DRAIN
LMS-15
GILA RIVER AND WELLTON-MOHAWK DRAINAGE
LMS-16
LMS-20
Ca++
HCO3-
Mg++
KEY
SO4--
Na+K+
Cl-
LMS-19
LMS-26
0 3 6 12 24
SCALE IN me/l
LMS-24

Figure 50 Ionic Concentration Diagrams for the Lower Main Stem Subbasin

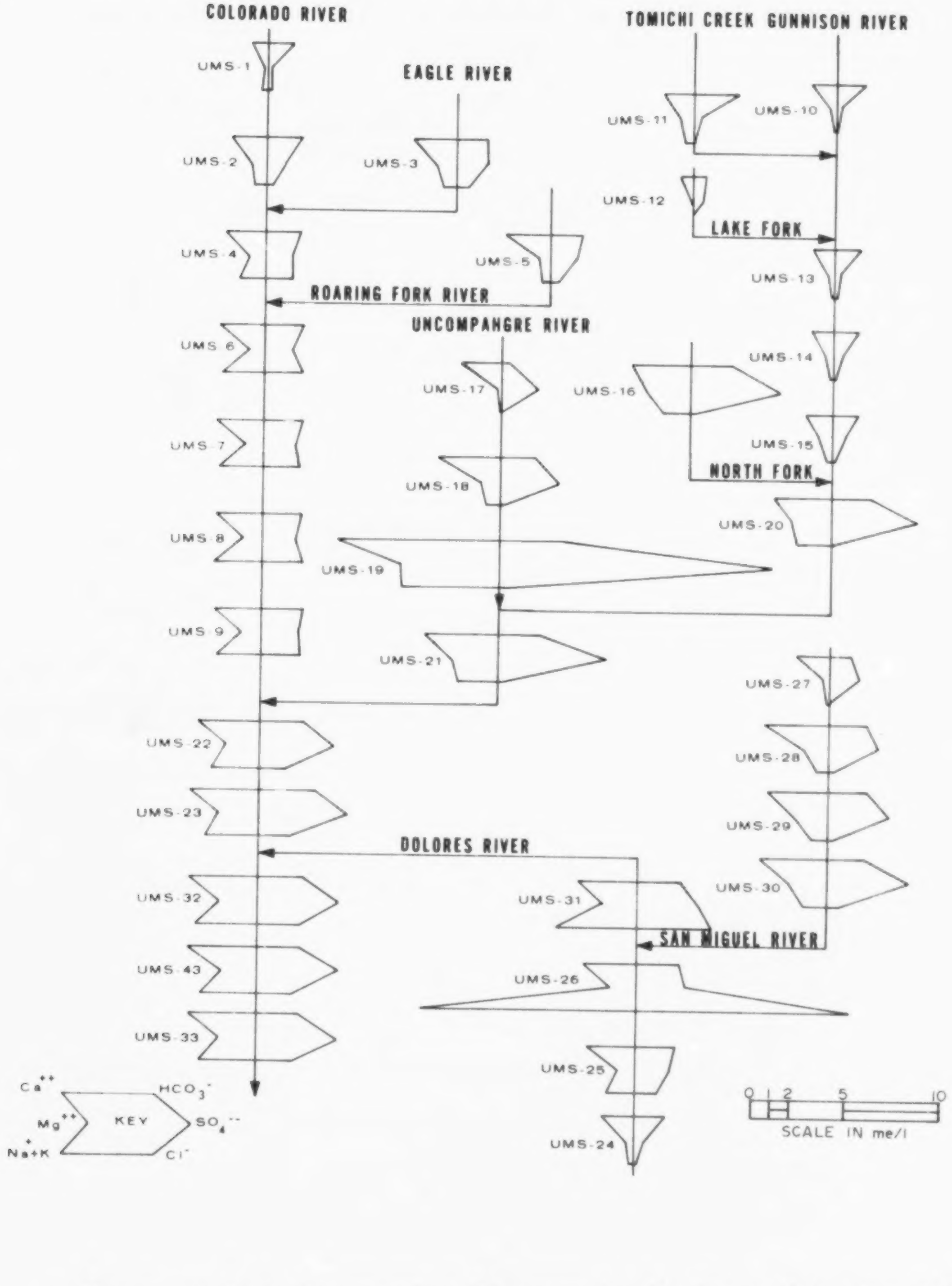

COLORADO RIVER
TOMICHI CREEK
GUNNISON RIVER
EAGLE RIVER
UMS-1
UMS-2
UMS-3
UMS-4
UMS-5
ROARING FORK RIVER
UMS-6
UMS-7
UMS-8
UMS-9
UMS-10
UMS-11
UMS-12
LAKE FORK
UMS-13
UMS-14
UNCOMPANGRE RIVER
UMS-17
UMS-16
UMS-15
NORTH FORK
UMS-18
UMS-20
UMS-19
UMS-21
UMS-27
UMS-22
UMS-28
UMS-23
UMS-29
DOLORES RIVER
UMS-30
UMS-31
UMS-32
SAN MIGUEL RIVER
UMS-43
UMS-26
UMS-33
UMS-25
UMS-24
Ca++
Mg++
Na+K
KEY
HCO3-
SO4--
Cl-
0 1 2 5 10
SCALE IN me/l

Figure 51 Ionic Concentration Diagrams for the Upper Main Stem Subbasin

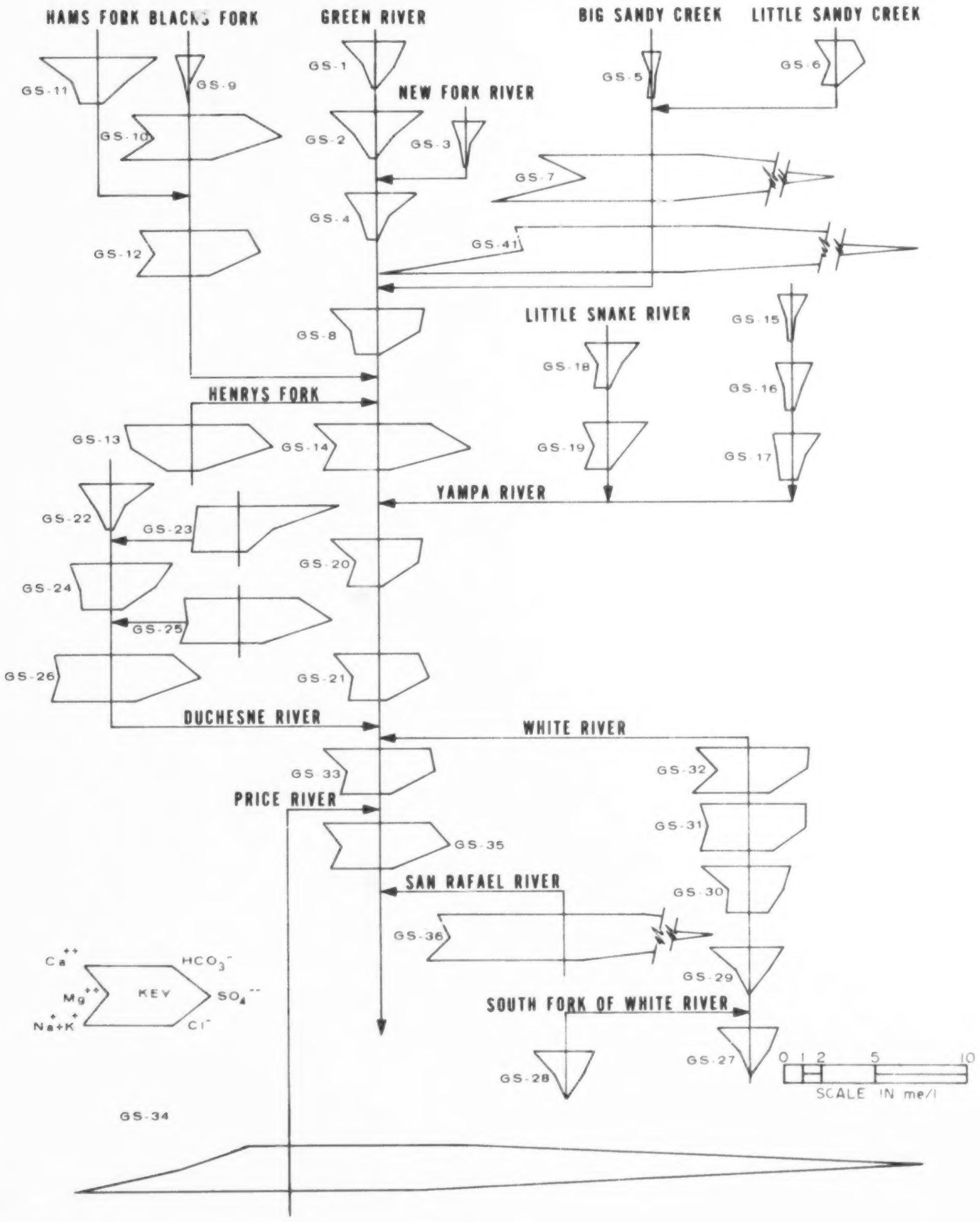

HAMS FORK
BLACKS FORK
GREEN RIVER
BIG SANDY CREEK
LITTLE SANDY CREEK
GS-11
GS-9
GS-1
GS-5
GS-6
NEW FORK RIVER
GS-10
GS-2
GS-3
GS-7
GS-4
GS-12
GS-41
GS-8
LITTLE SNAKE RIVER
GS-15
GS-18
GS-16
HENRYS FORK
GS-13
GS-14
GS-19
GS-17
YAMPA RIVER
GS-22
GS-23
GS-20
GS-24
GS-25
GS-26
GS-21
DUCHESNE RIVER
WHITE RIVER
GS-33
GS-32
PRICE RIVER
GS-31
GS-35
SAN RAFAEL RIVER
GS-30
GS-36
Ca++
HCO3-
Mg++
KEY
SO4--
Na++K+
Cl-
GS-29
SOUTH FORK OF WHITE RIVER
GS-27
GS-28
0 1 2 5 10
SCALE IN me/l
GS-34

Figure 52 Ionic Concentration Diagrams for the Green River Subbasin

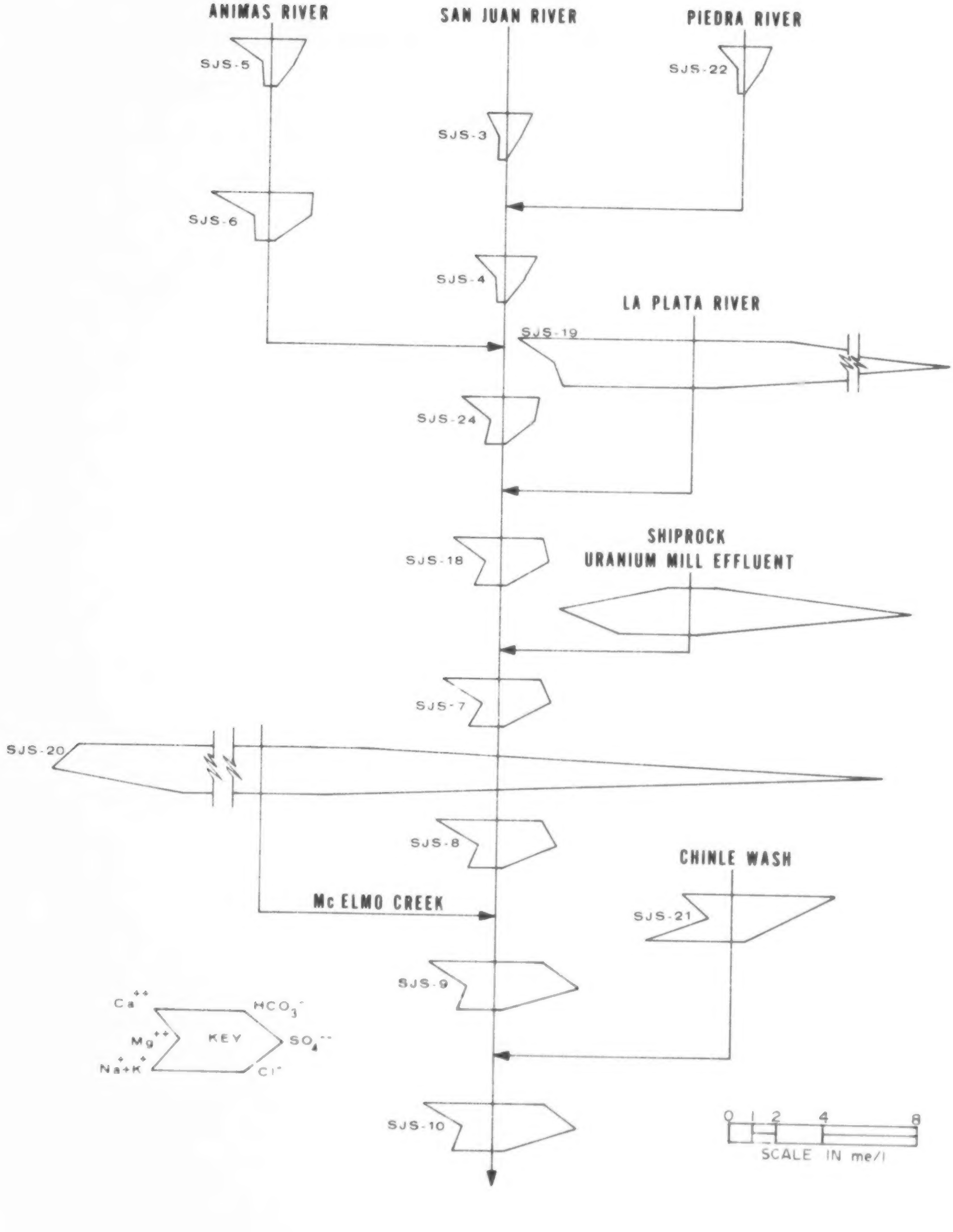

ANIMAS RIVER
SAN JUAN RIVER
PIEDRA RIVER
SJS-5
SJS-22
SJS-3
SJS-6
SJS-4
LA PLATA RIVER
SJS-19
SJS-24
SJS-18
SHIPROCK
URANIUM MILL EFFLUENT
SJS-7
SJS-20
SJS-8
CHINLE WASH
Mc ELMO CREEK
SJS-21
SJS-9
Ca^{++}
HCO_3^-
Mg^{++}
KEY
SO_4^{--}
$Na^+ + K^+$
Cl^-
SJS-10
0 1 2 4 8
SCALE IN me/l

Figure 53 Ionic Concentration Diagrams for the San Juan River Subbasin

District. These inputs were not of sufficient magnitude to significantly alter the chemical composition of the Colorado River. Large quantities of predominantly sodium-chloride type water discharged from the Wellton-Mohawk Main Outlet Drain caused the Colorado River water to become predominantly sodium-chloride type in the reach between the mouth of the Gila River and the Northerly International Boundary.

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